



Review

A Review of Eco-Friendly Road Infrastructure Innovations for Sustainable Transportation

Adamu Tafida ^{1,2,*}, Wesam Salah Alaloul ¹, Noor Amila Bt Wan Zawawi ^{1,3}, Muhammad Ali Musarat ^{1,3} and Adamu Sani Abubakar ⁴

- ¹ Department of Civil and Environmental Engineering, University Technology PETRONAS, Seri Iskandar 32610, Perak, Malaysia; wesam.alaloul@utp.edu.my (W.S.A.); ai.musarat@utp.edu.my (M.A.M.)
² Department of Quantity Surveying, Abubakar Tafawa Balewa University, Bauchi 740101, Nigeria
³ Offshore Engineering Centre, Institute of Autonomous System, University Technology PETRONAS, Seri Iskandar 32610, Perak, Malaysia
⁴ Department of Building, Abubakar Tafawa Balewa University, Bauchi 740272, Nigeria
* Correspondence: adamu_22000475@utp.edu.my

Abstract: Eco-friendly road infrastructure is vital for the advancement of sustainable transportation and promotion of efficient urban mobility. This systematic literature review explores the current state of research and development in the eco-friendly road infrastructure area. This review explored three electronic databases to gather pertinent studies using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. This study explored a wide range of research areas pertinent to eco-friendly road infrastructure. The findings highlight significant progress in the utilization of recycled materials, integration of photovoltaic, piezoelectric, and other energy harvesting technologies, regulatory frameworks, AI and machine learning for monitoring, predictive maintenance, and other technologies to enhance road sustainability and performance. This review analyzed the development of eco-friendly road infrastructure and identified several challenges such as high initial costs, technical performance issues, regulatory gaps, limited public acceptance, and the complexity of integrating advanced technologies. Addressing these challenges will require collaboration, further advancement in knowledge, and standardized regulations. This review serves to broaden the knowledge of the area and offer direction for future research and policy discussions, underscoring the need for continuous advancement in eco-friendly road infrastructure to meet sustainable development goals and address the challenges of climate change.

Keywords: eco-friendly road infrastructure; sustainable transportation; renewable energy integration; AI and machine learning (ML); environmental impact and mitigation



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1. Introduction

The continuous growth of urban populations has made transportation a significant contributor to environmental pollution. In 2011, transportation accounted for 25% of the European Union's total greenhouse gas emissions. Urban mobility alone was responsible for 40% of carbon dioxide (CO₂) emissions and up to 70% of other pollutants from the transport sector [1]. The Congressional Budget Office (CBO) stated that in the United States (US), nearly 80% of the overall emission of approximately 6.4 billion metric tons of greenhouse gases in 2021 were CO₂, with transportation accounting for 38% [2]. Likewise, road transport was said to have accounted for 81.1% of total transport carbon emissions in China and 93.5% in India [3]. The International Energy Agency (IEA) asserted that with the resurgence in passenger and cargo transport post-COVID-19, transport CO₂ emissions have increased compared to previous years. Addressing this issue will require concerted efforts, stringent regulations, fiscal incentives, and substantial infrastructure investments to promote sustainable transportation [3].

Research into advancing eco-friendly road infrastructure is vital for mitigating CO₂ emissions and achieving sustainable transportation in line with the United Nations Sustainable Development Goals (SDGs), specifically SDG 11 (Sustainable Cities and Communities), SDG 13 (Climate Action), and SDG 9 (Industry, Innovation, and Infrastructure) [4]. Sustainable transportation embodies the principles of sustainable development, focusing on environmental, economic, and social impacts [5,6]. This concept aims to reduce the negative impact of transportation on the environment and society while ensuring the efficiency and affordability of transportation systems [7]. Sustainable transportation requires a comprehensive approach that includes the adoption of alternative fuels, enhancement of public transportation, development of pedestrian and cycling infrastructure, and implementation of smart transportation management systems. By integrating these strategies, cities can reduce their environmental impact, improve public health, and promote economic and social well-being [8]. Sustainable transportation plays a key role in mitigating climate change, reducing carbon emissions, and promoting environmental stewardship [9]. This alignment has driven the demand for sustainable practices in transportation [10].

Similarly, eco-friendly infrastructure is a term that embodies sustainable principles across design, construction, and operation to mitigate environmental impact and foster long-term sustainability [11]. The concept integrates numerous strategies to minimize resource consumption, reduce pollution, and enhance community well-being. Energy efficiency measures, including the adoption of energy-saving technologies and renewable energy sources, play a central role in eco-friendly infrastructure projects [12]. In practice, the concept encourages sustainable material selection, with emphasis on the use of recycled, renewable, or sustainably sourced materials in projects, water conservation, and other resource conservation techniques [13,14]. Key characteristics and components of eco-friendly infrastructure as cited in literature include energy efficiency measures [15], sustainable material selection [16], water conservation strategies [17], waste reduction practices [18], integration of green spaces [19], low-impact design features, emphasis on sustainable transportation solutions, pollution control measures, climate-resilient designs, and integration of smart technologies [20].

Eco-friendly is often used interchangeably with green and sustainable because all of these concepts prioritize the well-being of the planet [21]. Campbell, Khachatryan [22] stated that sustainability takes a comprehensive view of human impact on the environment, society, and economy, aiming to minimize harm and prevent direct damage to the planet. In contrast, eco-friendliness focuses on individual actions to reduce environmental impact through conscious choices in product use, service consumption, and daily practices. While sustainability addresses systemic issues, eco-friendliness emphasizes immediate actions for environmental stewardship. Researchers have identified economic, social, and technological challenges in making road infrastructure more eco-friendly [23–25]. Innovations in transport infrastructure show a relationship between road infrastructure and population well-being, particularly regarding economic growth, improved accessibility, and enhanced quality of life [26–28]. However, without sustainable management, these benefits can lead to environmental degradation and health issues. Social sustainability and health impacts need more consideration in road infrastructure projects to ensure holistic improvements in population well-being [28]. Despite the recognized benefits and ongoing research, a gap remains in knowledge regarding the advancement of eco-friendly infrastructure. Previous studies have highlighted significant advancements in eco-friendly road infrastructure and their impact on sustainable transportation.

The critical issue of carbon emissions from road pavements, focusing on life cycle phases and identifying the use phase as the highest contributor to emissions was highlighted by Zhu Zhu, Li [29]. The study reviewed quantification methods, influential factors like pavement–vehicle interaction, and reduction technologies such as cool pavements and reflective pavements. Similarly, a framework that utilized the Gradient Boosting Decision Tree (GBDT) algorithm was used to assess the carbon footprint of urban road networks by Yu, Chen [30], and the findings suggested that material production accounts for 78% of

emissions in road construction. Their machine learning model was said to have accurately predicted material stocks, aiding in the design of carbon-neutral transport systems. Another study explored the advancements in construction material for eco-friendly road transportation by modifying materials such as crumb rubber to enhance asphalt high-temperature viscosity and storage stability with the incorporation of Vestenamer [31]. Research has explored alternative materials such as bitumen modified with high-content SBS polymers with the potential for superior resistance to rutting, fatigue, and cracking [32]. The modification was carried out to enhance the sustainability of the material, and the potential for recyclability of reclaimed asphalt (RA) pavements was investigated using modified FTIR to identify contaminants and enhance the usability of RA [33]. The research into the use of modified material, recycling, and other sustainable material has shown significant performance improvement results; however, scalability and practical application across different soil types under varied conditions is needed to aid adoption.

Research into the integration of technological advancements, such as AI, computer vision, machine learning, internet of things (IOT), and so on, with eco-friendly road infrastructure has shown potential for improving the sustainability of transportation networks. The application of technologies for improved road infrastructure maintenance and management have been studied by Yang, Zhang [34], Cano-Ortiz, Lloret Iglesias [35], and many other researchers. The road asset management tools and techniques cited have utilized a range of technologies such as drone [36], deep learning [37], computer vision and photogrammetry [35], and the like. However, despite the advancements in integration with these technologies, significant challenges remain in data collection, model optimization, and real-time performance, necessitating further research and development. Other innovations include non-destructive testing (NDT) technologies, such as ground-penetrating radar and infrared thermal imaging for asphalt pavements, which have been shown to offer better precision and future development trajectories [38].

Addressing this gap is crucial for improving road infrastructure and mitigating adverse environmental effects, thereby achieving sustainable transportation. In this context, this review synthesizes existing knowledge and identifies best practices to provide valuable insights into effective strategies for reducing environmental impact, enhancing resilience, and promoting sustainability in road construction and maintenance. This review supports informed decision-making and policy development, ensuring innovations are effectively integrated into current and future projects, thereby advancing sustainable transportation systems and addressing global climate challenges. To the best of the authors' knowledge, no previous reviews have combined all the pertinent research areas identified in this study. This study seeks to systematically review recent publications in the areas of eco-friendly road infrastructure for sustainable transportation. Specifically, the literature review consists of the following:

1. An analysis of the innovations and technologies employed in eco-friendly road infrastructure.
2. An assessment of how these innovations is being integrated into current road infrastructure projects.
3. Identification of the challenges and future directions in eco-friendly road infrastructure research.

This paper is structured as follows: Section 2 outlines the research methodology adopted for the review. Section 3 provides the results, summarizing all the reviewed literature with the aid of tables and figures. Section 4 discusses the literature included in the review based on research areas, highlighting innovative materials, methods, technologies, and policies for enhancing eco-friendly road infrastructure. Section 5 addresses the challenges and future directions. Section 6 discusses the strengths and limitations of this study. Finally, Section 6 summarizes the entire review, the contributions of this study, and concludes with final remarks.

2. Methodology

This chapter details the systematic search strategy and criteria employed based on the PRISMA guidelines to select studies on eco-friendly road infrastructure for sustainable transportation [39]. It includes the search process, inclusion and exclusion criteria, study selection process, and quality assessment to ensure the rigor and relevance of the reviewed literature.

2.1. Search Strategy

A systematic search of three electronic databases, namely Science Direct, SCOPUS, and Web of Science, was carried out to gather pertinent studies using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [40]. The search strategy entails the following three steps: (1) Identification of relevant keywords and phrases related to road sign comprehension. (2) Utilization of a combination of keywords and phrases using Boolean operators to construct search queries. Table 1 below summarizes the keywords, databases, and articles cited based on the search strategy. (3) The search results were screened based on title, abstract, and keywords to identify potentially relevant studies.

Table 1. Summary of databases and keywords selected.

S/NO	Keywords Searched	Scopus	Wos	Science Direct	Total
1	TITLE-ABS-KEY ("Eco-Friendly" AND "Road Infrastructure")	22	12	313	347
2	TITLE-ABS-KEY ("Sustainable Transportation "AND "Road Infrastructure")	27	9	430	466
3	TITLE-ABS-KEY ("Innovation" AND "Road Infrastructure" AND "Sustainable Transportation")	1	9	160	170
		50	30	903	983

2.2. Inclusion and Exclusion Criteria

The inclusion criteria for this study encompass studies on eco-friendly road infrastructure for sustainable transportation. The selected studies are papers published in peer-reviewed journals and conference proceedings, made available in English, and published between 2013 and 2024. Studies not in the subject area were excluded. Furthermore, grey literature sources such as reports, books, book chapters, theses, dissertations, and protocols were excluded, along with studies not available in English.

2.3. Study Selection Process

Two trained independent reviewers examined the titles, abstracts, and full texts of studies to identify the publications that potentially fulfilled the inclusion criteria based on the PRISMA guidelines. The study selection process comprised four stages: First, an initial screening of search results was conducted based on keywords, titles, and abstracts to identify potentially relevant studies. Subsequently, selected studies underwent a full-text assessment to establish their eligibility, guided by the predefined inclusion and exclusion criteria. The studies that fulfilled the inclusion criteria were selected for data extraction and synthesis. Finally, any differences that arose throughout the selection process were resolved by discussion and consensus among the reviewers, guaranteeing consistency and accuracy in study selection. Figure 1 displays the flow chart of the selection procedure.

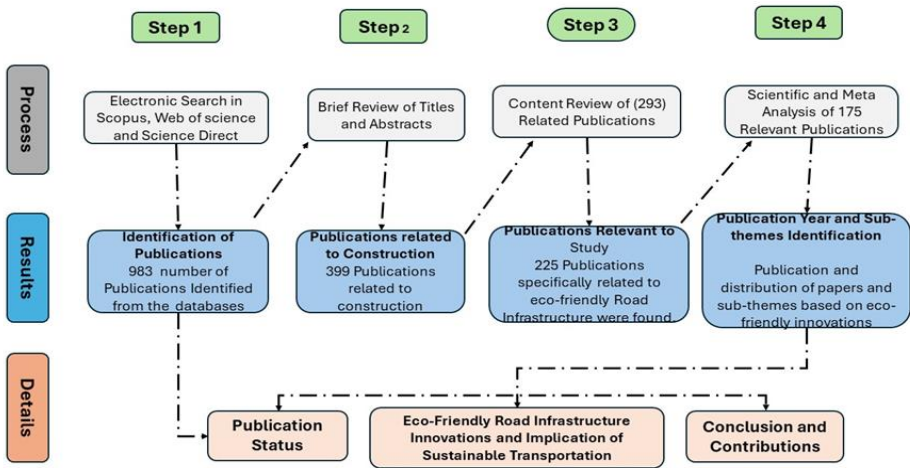


Figure 1. Flow chart of the selection procedure using the PRISMA guidelines.

2.4. Quality Assessment

Quality assessment is a crucial part of this review, as it evaluates the validity, reliability, and overall quality of the included studies. The criteria used for quality assessment in this study include the following: Author/Journal/Year provides information about the publication; Objectives assesses the clarity and relevance of the study objectives; Validity evaluates the internal and external validity of the study; Reliability examines the consistency and repeatability of the findings; Number of Citations indicates the impact and recognition in the field; and Quartile is based on the journal’s ranking by impact factor. Table 2 highlights the quality assessment criteria with examples while Figure 2 shows a summary of the included journal rankings in Scopus and Clarivate.

Table 2. Quality assessment criteria [41].

Author/Year	Objectives	Validity	Reliability	Citations	Quartile
The citation is extracted and considered	Did the research have a clear objective relating to eco-friendly road infrastructure?	To what extent did the research accomplish its aims? (rate from high to low)	Likelihood of being able to replicate the findings? (rate from high to low)	How many citations does it have?	What is the ranking of the journal?
Example: Yu et al., 2024	Example: Carbon footprint of urban road networks	Example: High	Example: High	Example: 136	Example: Q1

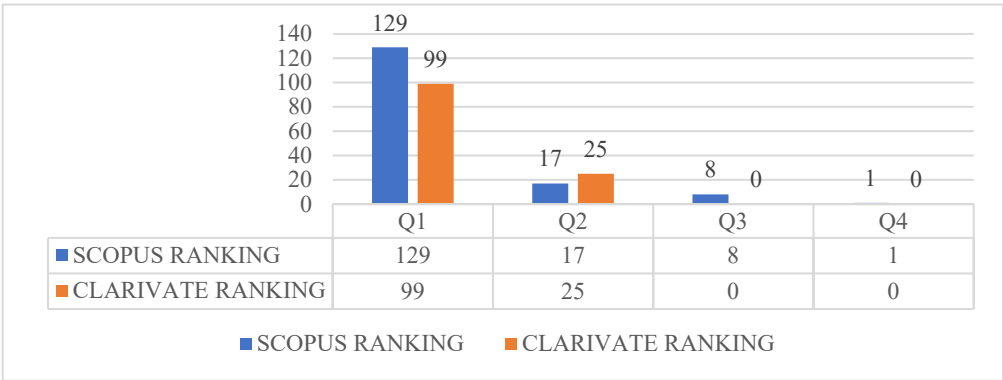


Figure 2. Ranking of included journal article sources.

Figure 2 below shows that out of the 175 articles included in the review, 129 were in Scopus Quartile 1 (Q1) journals while 99 were found in Clarivate Q1 journals. The

proportion of articles in journals ranked Q1 in Scopus and Clarivate (73%/55%) highlights the quality of the articles reviewed.

3. Results

This section provides a summary of the search results, study characteristics, sources, and attributes of articles and other characteristics of the selected articles. It offers an overview of the prevalent themes and terminologies within the field, systematically categorizing the research areas in eco-friendly road infrastructure and the characteristics of the data. This categorization sets the stage for a detailed and nuanced analysis. By highlighting the major themes and terminologies, this summary facilitates a comprehensive understanding of the current state of research in eco-friendly road infrastructure, laying the groundwork for further exploration and interpretation.

3.1. Search Results

This study's search strategy yielded a total of 983 articles. After removing duplicates, there were 942 unique articles left. These articles were screened for eligibility, yielding 399 full-text articles for consideration. A total of 106 articles were excluded during the content review because they were not directly related to eco-friendly road infrastructure, and 48 full articles were not in English. Finally, following the screening process, 175 eligible articles were included in this study.

3.2. Sources and Characteristics of Journal Articles

This section delves into the origins and key attributes of the journal articles analyzed. It provides an overview of the publication sources and highlights the significant characteristics that inform this review of eco-friendly road infrastructure innovations. Table 3 shows the title of journals with up to two included articles. The *Construction and Building Materials* journal, with the highest number of articles, has an impressive cite score and impact factor. The *Journal of Applied Energy* had the highest cite score and impact factor with three included articles. In summary, the journal titles and scope underline the prominence of materials research as seen in the research trends shown in Figure 3, and the eco-friendly transportation inclinations to renewable energy, automation, and other advancements in technology.

Table 3. Top 10 journals based on the selected articles.

S/No	Title of Journal	Articles Per Journal	Cite Score	Impact Factor
1	<i>Construction and Building Materials</i>	55	13.8	7.4
2	<i>Journal of Traffic and Transportation Engineering</i> (English Edition)	4	13.6	7.9
3	<i>Case Studies in Construction Materials</i>	4	7.6	6.2
4	<i>Journal of Road Engineering</i>	3	5.1	-
5	<i>Transportation Research Interdisciplinary Perspectives</i>	4	12.9	-
6	<i>Journal of Building Engineering</i>	3	10.0	6.4
7	<i>International Journal of Transportation Science and Technology</i>	3	7.2	-
8	<i>Advanced Engineering Informatics</i>	2	12.4	8.8
9	<i>Procedia CIRP</i>	3	3.8	
10	<i>Renewable Energy</i>	3	18.4	8.7

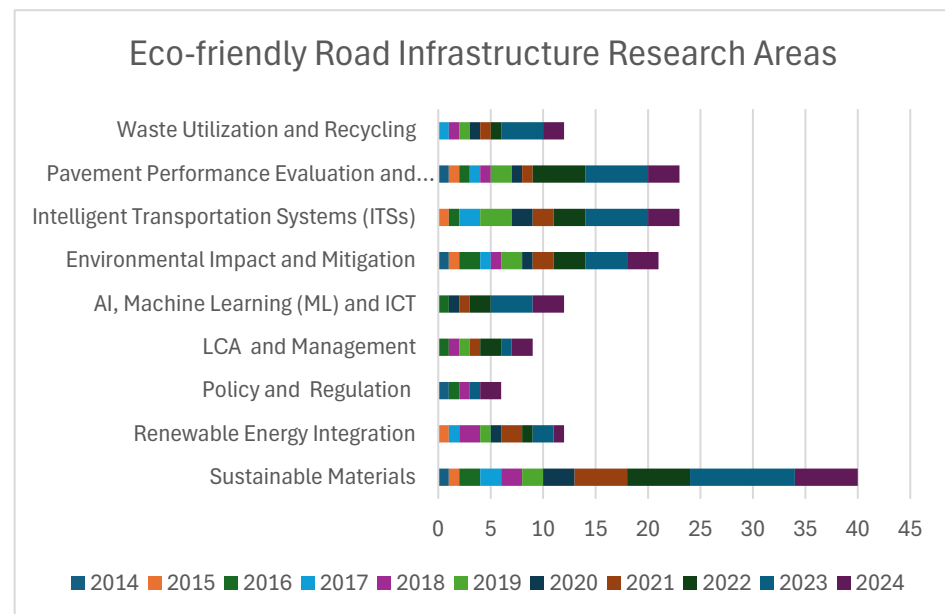


Figure 3. Eco-friendly road infrastructure research areas cited in the reviewed articles.

The systematic literature review identified the main research areas for eco-friendly road infrastructure aimed at sustainable transportation, spanning several domains. These areas include sustainable materials, focusing on advancing the use of environmentally friendly materials; pavement performance evaluation and road asset management, which involves innovations to enhance the durability and lifespan of pavements; and Intelligent Transportation Systems (ITSs), which explore smart technologies to improve traffic management, safety, and reduce congestion and emissions. Additionally, research on environmental impact and mitigation aims to reduce pollution and conserve natural habitats. The review also covers advancements in artificial intelligence (AI), machine learning (ML), and information and communication technology (ICT), as well as life cycle assessment (LCA) and management practices considering the entire life cycle of materials. Policy and regulation research emphasizes the development of policies to promote sustainable practices. Lastly, the review includes studies on waste utilization and recycling, and the integration of renewable energy into road infrastructure. Table 3 and Figure 3 highlighted the research areas based on area, year, and number of articles. The figure indicates that the research area of sustainable materials has received significant attention, while the area of policy and regulation has the least traction in terms of eco-friendly road infrastructure research for sustainable transportation.

3.3. Summary of Journal Articles Included in the Review

This study included a substantial body of literature from various high-quality sources to support the objectives of the review of eco-friendly road infrastructure innovations. The articles spanned a wide range of research areas pertinent to eco-friendly road infrastructure, including sustainable materials, renewable energy integration, policy and regulation, life cycle assessment (LCA) and management, AI and machine learning (ML), environmental impact and mitigation, Intelligent Transportation Systems (ITSs), pavement performance evaluation, and waste utilization and recycling. Table 4 highlights the articles included in the systematic review, presenting their focus, key findings, and identified gaps.

Table 4. Summary of articles included in the literature review.

S/No	Study	Focus	Key Findings	Research Gaps
1	Yu et al., 2024	Machine learning (GBDT) prediction model, case study of Nanjing	Framework assesses carbon footprint of urban road networks from production to maintenance; model predicted 2021 material stock with <2% error	Model validation is limited to Nanjing; needs broader application to confirm effectiveness
2	S. Yang et al., 2024	Incorporation of sodium hydroxide pre-treated crumb rubber and Vestenamer TOR	Investigated performance of composite-modified asphalt with pre-treated crumb rubber; Vestenamer TOR improved cracking resistance;	Further research is needed on long-term performance and large-scale application
3	Wetekam and Mollenhauer, 2024	Modified FTIR method for identifying substances in reclaimed asphalt	The FTIR method identifies PAH-contaminated samples, SBS modification, viscosity-changing organic additives in RA	Further validation and refinement needed to enhance accuracy and reliability
4	Vinodhini and Sidhaarth, 2024	Detection of potholes using transfer learning, CNN	The proposed method achieves 96% accuracy in detecting potholes: valuable for ITS services and road management systems	Comparison with other state-of-the-art detection algorithms needed
5	Siva Rama Krishna et al., 2024	Optimization of inverted pavement using the Box–Behnken method, LCCA/LCA	Studied critical factors affecting inverted pavement performance; optimized pavement thickness/material properties; and demonstrated benefits in cost and carbon emissions reduction	Validation in diverse traffic and environmental conditions required; comprehensive long-term performance analysis needed
6	Shan et al., 2024	Multimodal data fusion for road infrastructure perception	Proposed lightweight neural network for multimodal image segmentation; improved segmentation of road materials, and mIoU index improved by 4.2% compared to RGB images	Practical implementation and scalability of multimodal data fusion methods
7	Que et al., 2024	Macroscopic and microscopic experiments on soil tuff-modified tailings	Demonstrated soil tuff’s effectiveness in improving lead–zinc tailings as subgrade fillers; enhanced structural stability,	Long-term performance validation required; broader comparison with other modification methods needed
8	Puma et al., 2024	Case studies on material reuse (structural steel and slag) in construction	Highlighted benefits of reclaimed steel and slag in waste reduction; showcased eco-friendly housing, adaptive reuse, asphalt applications; and promoted circular economy principles	Comparison with other sustainable construction practices and scalability required
9	Ouni and Ben Abdallah, 2024	ARDL bounds test and VECM Granger causality test in Tunisia’s transport sector	Analyzed relationship between poverty, economic growth, energy consumption, urbanization, trade openness, and road infrastructure	Focused on Tunisia

Table 4. *Cont.*

S/No	Study	Focus	Key Findings	Research Gaps
10	Nandi et al., 2024	Utilization of RAP aggregates in precast concrete paver blocks (CPBs)	Studied wollastonite and jarosite as cement substitutes; improved flexural strength, tensile splitting strength, abrasion resistance	Limited improvement in compressive strength, permeable voids, and water absorption
11	Q. Liu et al., 2024	Life cycle assessment framework for quantifying carbon emissions	Introduced practical model system for capturing CEs across asphalt pavement lifespan	Variation in emission estimates for construction machinery
12	Kurniawan et al., 2024	Case study, comparative analysis of digitalization-based waste recycling	Digital revolution in Hainan achieved 90% waste avoidance through optimized recycling and decreased GHG emissions	Implementation in Lombok depends on socio-economic conditions and digital readiness
13	W. Jiang et al., 2024	Experimental study using Fluorescence Microscopy, FTIR	Polyurethane-modified asphalt exhibits superior thermal performance, cryogenic stability, and improved flexibility	Long curing reaction time and resting conditions for optimal results
14	Jahanbakhsh et al., 2024	Experimental evaluation using mechanical testing and Gray Relation Analysis (GRA)	Conductive additives like steel slag improve mechanical properties and heating rates of asphalt; steel slag mixtures are more sustainable and cost-effective	Conductive materials for enhanced sustainability
15	Hatami-Marbini et al., 2024	Nonparametric frontier analysis (Data Envelopment Analysis) to measure environmental performance in transport	EU countries' transport sector emissions are major contributors to global emissions; top methodologies include Data Envelopment Analysis and emission analysis	Comprehensive environmental performance assessment
16	Guo et al., 2024	Custom-designed dynamic water scouring simulation apparatus, GM (1,N) damage prediction model	Combined salt erosion and dynamic water scouring significantly impact short-term performance of asphalt; CH ₄ N ₂ O has the most pronounced effect on water damage	Need for more studies on long-term effects and mitigation strategies for salt erosion and dynamic water scouring
17	Fadugba et al., 2024	Experimental tests on citric acid-treated natural fibers in soil	Sawdust-treated soil exhibits significant improvements in density, compressive strength, shear strength, and CBR	Exploration of other natural fibers and treatment methods
18	Elassy et al., 2024	Examination of Intelligent Transportation System (ITS) components and recent advancements	ITS components like Vehicular Ad hoc Networks and intelligent traffic lights improve transport efficiency and safety; case studies demonstrate benefits in urban areas	Security and privacy challenges need to be addressed

Table 4. Cont.

S/No	Study	Focus	Key Findings	Research Gaps
19	Deo et al., 2024	Laboratory investigation using reflectance spectroscopy for moisture and diesel detection	Reflectance spectroscopy effectively detects moisture and diesel on asphalt; binary formulations developed for practical assessment	Development of real-time monitoring technologies
20	Cervantes Puma et al., 2024	Case study analysis of material reuse in construction	Reclaimed structural steel and slag reduce waste, conserve energy, and lower GHG emissions; demonstrated benefits in eco-friendly housing and road construction	Challenges in material recovery due to building design
21	Cano-Ortiz et al., 2024	Development of public dataset and deep learning models for road assessment	Proposed dataset enhances model training for defect detection; YOLOv5 sub-models optimized for detection efficiency; and new pavement condition index (ASPDI) aids in maintenance decision-making	Limited availability of real-world datasets
22	Bhalerao et al., 2024	Development of HCV emission inventory for India based on stakeholder inputs	Introduction of BS-VI standards and anticipated BS-VII standards significantly reduce emissions by 2035; efficient commercial vehicle usage improves despite marginal increase in HCV population	Consideration of other vehicle types and transport modes for comprehensive pollution reduction strategies
23	Adresi et al., 2024	Evaluation of different weigh-in-motion (WIM) systems	Various WIM systems and sensors enhance vehicle weight measurement accuracy; potential applications in traffic monitoring and road safety improvements	Analysis of WIM systems under different road and traffic conditions
24	Zhu et al., 2023	Mechanical tests, interfacial adhesion tests, and Digital Image Correlation	Self-adhesive basalt fiber mesh geotextiles enhance asphalt pavement strength and crack resistance; maximum tensile strength of 3.599 kN, 34% higher than plain fabric; and improved adhesion to asphalt by 14.54%	Need for real-world testing to validate lab results
25	Zhang et al., 2023	Material flow and stock analysis; ARIMAX, SVR, hybrid ARIMAX-SVR, MLR, ANN, and RF models for forecasting	Japan's total road material stock increased 5.5-fold from 1965 to 2020; aggregate dominated materials; forecasting revealed varied patterns across regions; and SSP5 scenario showed the highest expected road material stock	Limited to Japan; forecasting accuracy depends on the model and scenarios used
26	Xing et al., 2023	Atomic Force Microscopy (AFM) and PF-QNM mode for nanomechanical properties analysis	Internal phases of SBS-modified bitumen identified, no new phases created, but existing phases' proportions altered; addition of fillers slightly changed phase distribution	Focus on lab-scale analysis; real-world implications need further investigation
27	Wulandari et al., 2023	Marshall test method, comparison of four types of emulsified asphalt	CRS-2 not recommended due to low stability; CQS-1h recommended for heavy traffic in Indonesia for high stability at early age	Limited to Indonesia

Table 4. *Cont.*

S/No	Study	Focus	Key Findings	Research Gaps
28	Wang et al., 2023	Mapping of material stock, analysis of spatial planning and recycling	Spatial planning can reduce road material stocks and associated GHG emissions; urban mining and recycling can significantly cut emissions	Focus on Belgium; need for broader application and validation in different contexts
29	Vescovi et al., 2023	Evaluation of IOT as supplementary cementitious material	IOT as a partial replacement for clinkers in Portland cement is viable, improving sulfuric acid resistance and reducing CO ₂ emissions	Variation in IOT composition impacts results
30	Slebi-Acevedo et al., 2023	Experimental PA mix evaluation, statistical analysis, PCA, AHC	PA mixes with up to 28% air voids can meet resistance requirements: use of PMB, fibers, and hydrated lime essential for improved mix formulation	Performance data: specific climate conditions not addressed
31	Silva et al., 2023	UAV images, deep learning for road damage detection	YOLOv7 achieved 73.20% mAP@.5, demonstrating high efficiency and accuracy in road damage detection	Need for broader dataset
32	Shanmugasundaram and Shanmugam, 2023	OPC addition to MMT, various strength and durability tests	OPC addition increases strength of OPC-MMT mixes; stabilized mixes meet environmental limits and show improved durability	Environmental impact of higher cement use not fully explored
33	Roja et al., 2023	Performance evaluation of asphalt mixtures, Circly, PerRoad, and MEPD methods	Stiff mixes with PG 82E-10 binder beneficial for medium traffic levels; French EME mix recommended for base layers in heavy traffic roads	Specific to Qatar
34	Ranjbar et al., 2023	Development of a drone-based platform for road monitoring, computer vision techniques	Effective road detection and segmentation using UAVs, with optimized real-time processing capabilities	Evaluation limited to urban areas; broader application needed
35	Polo-Mendoza, Mora et al., 2023	Life cycle assessment (LCA) and life cycle cost analysis (LCCA) for pavement alternatives	Perpetual pavements (PPs) offer less environmental damage and higher cost-efficiency compared to Conventional Flexible Pavements (CFPs) and Conventional Rigid Pavements (CRPs)	Case study limited to Barranquilla, Colombia
36	Polo-Mendoza, Martinez-Arguelles et al., 2023	Proposal and evaluation of WMA-RCA mix design methods	WMA-RCA mixes can improve sustainability, but optimal design conditions need careful adjustment due to RCA's impact on mix properties	Need validation of proposed methods
37	Makoundou et al., 2023	Laboratory and field tests, evaluation of mechanical properties	Developed a cold, highly rubberized asphalt mixture that reduces fall-related injuries and retains performance over time; significant improvement in impact-attenuation and durability	Future research needed for large-scale implementation and long-term maintenance
38	Majdoubi et al., 2023	Preparation and testing of geopolymer-reinforced PG composites	Enhanced mechanical properties and self-healing capabilities due to PG addition; developed composites exhibit lower heavy metals leaching	Long-term performance and broader industrial applications

Table 4. *Cont.*

S/No	Study	Focus	Key Findings	Research Gaps
39	Lu et al., 2023	Development and testing of self-cleaning pavement coatings	Hydrophobically modified TiO ₂ and silicone resin enhance self-cleaning and environmental performance.	Permeability is affected by SCPC spraying
40	Liu et al., 2023	Development and testing of eco-friendly materials using RBP and FBCF	EFMSIB material demonstrates significant strength and self-consolidation properties, effective heavy metal containment	Long-term performance and large-scale applicability
41	Licitra et al., 2023	Acoustic performance evaluation using the CPX method	Variability in acoustic performance of pavements; potential for optimization in road asset management	Need for broader dataset and extended analysis
42	Lee et al., 2023	Fatigue and reflection crack performance tests, evaluation of modified asphalt mixtures with epoxy and crumb rubber	Modified asphalt mixtures show improved fatigue crack resistance and reduced load reduction; optimal for aged concrete overlays	Long-term performance and large-scale implementation need further study
43	Kumar et al., 2023	Preparation and testing of e-waste-modified bitumen, evaluation of physical and rheological properties	Optimal 2.5 wt% e-waste improves blending and rheological properties of bitumen, meeting VG40 standards	Need for large-scale implementation and environmental impact assessment
44	Makoundou et al., 2023	Laboratory and field tests, evaluation of mechanical properties	Developed a cold, highly rubberized asphalt mixture that reduces fall-related injuries and retains performance over time;	Implementation and long-term maintenance
45	Majdoubi et al., 2023	Preparation and testing of geopolymer-reinforced PG composites	Enhanced mechanical properties and self-healing capabilities due to PG addition; developed composites exhibit lower heavy metals leaching	Broader industrial applications
46	Lu et al., 2023	Development and testing of self-cleaning pavement coatings	Hydrophobically modified TiO ₂ and silicone resin enhance self-cleaning and environmental performance.	Permeability is affected by SCPC spraying
47	Liu et al., 2023	Development and testing of eco-friendly materials using RBP and FBCF	EFMSIB material demonstrates significant strength and self-consolidation properties, effective heavy metal containment	Long-term performance and large-scale applicability
48	Licitra et al., 2023	Acoustic performance evaluation using the CPX method	Variability in acoustic performance of pavements, potential for optimization in road asset management	Need for broader dataset and extended analysis
49	Lee et al., 2023	Fatigue and reflection crack performance tests, evaluation of modified asphalt mixtures with epoxy and crumb rubber	Modified asphalt mixtures show improved fatigue crack resistance and reduced load reduction, optimal for aged concrete overlays	Long-term performance and large-scale implementation need further study
50	Kumar et al., 2023	Preparation and testing of e-waste-modified bitumen	Optimal 2.5 wt% e-waste improves blending and rheological properties of bitumen, meeting VG40 standards	Environmental impact assessment

Table 4. *Cont.*

S/No	Study	Focus	Key Findings	Research Gaps
51	Kashaganova et al., 2023	Study of fiber-optic sensors based on fiber Bragg grating for road surface monitoring	Improved accuracy in monitoring deformation, stress, displacement, and temperature; reliable for road surface monitoring and predicting pavement service life	Long-term application in different environmental conditions
52	Jiang et al., 2023	Uniaxial compression test, MMLS3 accelerated loading test, and full-scale finite element simulation	ASP pavement structure (SMA-13, Q345D steel, ABS plastic) demonstrates superior strain behavior and load-bearing capacity, enhancing road durability	Long-term performance and large-scale implementation require further research
53	Huang et al., 2023	Performance characterization tests, high temperature dynamic water scouring experiment	DFPM with de-icing agents and fibers shows good permeability and de-icing properties; recommended for practical applications	Further research needed for long-term performance under different climatic conditions
54	Hossain, 2023	Proposal of underground maglev transportation infrastructure	Innovative maglev system proposed for zero greenhouse gas emissions and improved sustainability	Development for practical implementation required
55	Gaudenzi et al., 2023	Overview of lignin use in bituminous binders, LCA analysis	Lignin is a viable renewable material for bituminous pavements with environmental benefits	Multi-scale approach and further field application
56	Fagerholt et al., 2023	Mixed-method approach, interviews, surveys, and workshops	Identified drivers and barriers for CCAM deployment in Norway, provided policy recommendations	Strategies and increased cooperation in CCAM deployment
57	Dziedzic and Glinicki, 2023	Experimental tests on concrete mixtures, evaluation of ASR-induced expansion	Use of marginal fine aggregates and blast furnace slag improves concrete durability	Need for further studies on long-term effects and broader applications
58	Dulaimi et al., 2023	Investigation of CAEM properties, use of waste alkaline solutions and GGBFS	GCAE with waste alkaline solution shows potential for improved performance and sustainability	Further research needed for practical application and performance validation
59	Dong et al., 2023	Laboratory tests on lignin-stabilized loess	Lignin improves loss of strength and stability, suitable for soil modification	Performance in different environmental conditions
60	Din et al., 2023	Analysis of the relationship between road transportation and environmental sustainability	Road infrastructure and density positively impact environmental sustainability, while road transportation energy consumption and energy intensity negatively affect it	Sustainable transportation solutions and policies needed in densely populated areas
61	Deb and Singh, 2023	Laboratory tests on CMA with FA and RHA fillers, evaluation of Marshall stability	Replacing SD with RHA and FA improves Marshall stability, tensile strength, and moisture susceptibility; FA is the most cost-effective filler	Need for large-scale implementation and further cost analysis
62	de Medeiros et al., 2023	Physical analyses, SUPERPAVE design, and mechanical performance tests	Asphalt mixtures with marble and granite waste show superior mechanical performance, similar production costs to control mixtures	Further research on long-term performance and environmental impact

Table 4. *Cont.*

S/No	Study	Focus	Key Findings	Research Gaps
63	Das et al., 2023	Proposal and evaluation of Qi-ACO algorithm for sustainable 4DTSP with emission constraints	Qi-ACO algorithm effectively balances travel costs and emissions, suitable for sustainable transportation planning	Testing and adaptation in different fields like ship routing and supply chain problems
64	Covilla-Varela et al., 2023	Evaluation of RCA in HMA and WMA, performance tests LCA and LCCA	15% RCA content in asphalt mixtures is optimal for mechanical performance and cost-effectiveness; higher amounts cause deterioration	Assessment of different RCA sources and long-term performance
65	Zahid et al., 2022	Experimental investigation of nanomaterials (CNT and NC) in HMA	CNT and NC enhance dynamic modulus, stability, rut resistance, and moisture resistance; optimal mix: 1.5% CNT and 6% NC	Need for field validation and assessment of long-term performance
66	Yan et al., 2022	Experimental evaluation of ERB- and WCO-modified asphalt, various performance tests	ERB and WCO improve high- and low-temperature stability, water stability, and aging resistance; optimal mix: 4% WCO + 18% ERB	Further research on long-term durability and large-scale applications
67	Vakili et al., 2022	Assessment of lignosulfonate and polypropylene fiber in marl soil	Lignosulfonate and PP fibers improve soil durability and mechanical characteristics, forming stronger bonds	Need for field testing and long-term performance evaluation
68	Tchappi et al., 2022	Development of a dynamic traffic model using the holonic multilevel approach, simulation scenarios	Proposed model improves simulation accuracy and computational efficiency	Requires validation in real-world traffic systems and more complex scenarios
69	Strieder et al., 2022	Laboratory and field tests on pervious concrete with CDW, analysis of mechanical and hydraulic properties	RCA improves hydraulic properties but reduces mechanical behavior; field performance mostly consistent with lab results	Need for stricter control of material properties and long-term performance assessment
70	Sha, Jiang et al., 2022	Analysis of HZMB pavement design, construction, and operation challenges	Proposes GMA-10 + SMA-13 for steel deck, warm-mix flame retardant asphalt for tunnels, and BJ200 for expansion joints	Requires further field validation and adaptation for other sea-crossing infrastructures
71	Rust et al., 2022	Evaluation of substandard materials with nano-silane-modified bitumen emulsions	Stabilization with nano-silane-modified bitumen emulsion is cost-effective and reduces construction effort	Need for broader application and long-term performance evaluation
72	Rebelo et al., 2022	Data mining techniques for predicting ITSR of asphalt mixtures, sensitivity analysis	SVM is the best predictive model, binder content most influences water sensitivity	Further research on other influencing parameters and broader dataset validation
73	Polo-Mendoza et al., 2022	Life cycle assessment (LCA) and statistical analysis to determine optimal RCA content in WMA	Established a methodology to optimize WMA design with RCA, identified variables affecting environmental impact	Environmental evaluations of RCA in WMA to avoid excessive RCA content

Table 4. *Cont.*

S/No	Study	Focus	Key Findings	Research Gaps
74	Pamucar et al., 2022	Ordinal priority approach under picture fuzzy sets (OPA-P), case study, and validation analysis	Developed OPA-P to rank sustainable freight transportation alternatives, validated model stability	Need for further real-world application and validation in different contexts
75	Omur et al., 2022	Comparative study of NaOH and KOH as alkaline activators for slag mortars	KOH improves fluidity and compressive strength, NaOH reduces setting time and shrinkage; both activators' higher molarity decreases porosity	Need for further research on long-term durability and field performance
76	Mushtaq et al., 2022	Response surface methodology (RSM) based on the Box–Behnken design to optimize polymer-modified asphalt mixtures	PE polymers improved Marshall characteristics compared to PET; RSM effectively optimized polymer content for better performance	Need for large-scale application and long-term performance studies
77	Mazhoud et al., 2022	Laboratory tests, simulations, and finite element models for integrating wireless inductive charging in pavements	Validated mechanical behavior of pavement with inductive charging, identified overheating risks	Need for further investigation into overheating and long-term performance
78	Li et al., 2022	PSO-GRU neural network for predicting pavement performance, analysis with RF algorithm	PSO-GRU model improves prediction accuracy, effective for pavement quality index prediction	Need for broader dataset validation and real-world implementation
79	Kumari et al., 2022	Life cycle cost analysis (LCCA) and Environmental Impact Analysis (EIA) of concrete and asphalt roads	Concrete roads are 20% more economical over 30 years, have lower maintenance and environmental impact	Need for more detailed environmental impact assessments and broader regional studies
80	Kleizienė et al., 2022	Evaluation of nanoSiO ₂ and nanoTiO ₂ in rejuvenators for aged PMB, physical and rheological tests	Improved soft bitumen with 6% nanoTiO ₂ showed promising results for long-term aging resistance	Need for further validation on rejuvenator 's ability to restore SBS and protect from degradation
81	Jamal and Giustozzi, 2022	FTIR spectroscopy and rheological tests on UV and PAV-aged neat and crumb rubber-modified bitumen (CRMB)	CRMB enhances aging resistance against UV and PAV, limiting level of aging	Further research on long-term field performance and impact of different environmental conditions
82	Ingrassia and Canestrari, 2022	Fatigue behavior comparison of bio-asphalt and conventional mixtures, VECD analysis	Bio-asphalt showed less severe long-term aging, benefits in fatigue performance	Need for field validation and comparison of life cycle costs
83	Hou et al., 2022	Long-term monitoring and deep learning models	Deep learning models outperform traditional methods, BiLSTM-CNN achieves highest prediction accuracy	Application and validation in different infrastructure projects
84	Hamla et al., 2022	Modeling mechanical and physical tests, SEM, and XRD analysis on RCSC	High DS and CS rates in RCSC improve compressive and tensile strengths, increase compactness	Need for broader application and long-term performance studies

Table 4. *Cont.*

S/No	Study	Focus	Key Findings	Research Gaps
85	Gulisano et al., 2022	Investigation of piezoresistive behavior of conductive asphalt with EAFS and GNPs	Asphalt with EAFS and 7 wt% GNPs exhibited excellent self-sensing properties for traffic monitoring	Real-world application and long-term performance
86	Barbieri et al., 2022	Repeated load triaxial and cyclic triaxial tests, rolling bottle test on synthetic fluid-treated aggregates	Synthetic fluid significantly improves mechanical properties and water resistance of aggregates	Need for further field validation and long-term performance studies
87	Autelitano et al., 2022	Laboratory and full-scale validation of bio-based thermo-sensitive NaCl brine for anti-icing	Bio-based saline hydrogel effectively fills surface voids without permeating, maintaining pavement friction	Long-term performance evaluation
88	Adjei et al., 2022	Survey and analysis of social acceptance of e-mobility in Ghana	High demand for electrically powered motorbikes, significant factors influencing social acceptance identified	Assessment of long-term social acceptance and usage patterns
89	B. Yang et al., 2021	Cantabro tests, leaching tests on porous asphalt mixtures with various fillers	Diatomite and bauxite residues improve raveling resistance; asphalt film reduces metal pollutant leaching	Environmental impact of industrial solid wastes in porous asphalt pavements
90	Wang et al., 2021	Analysis of hydration and distribution of luminescent powder in SLCCM	Optimal LP content (20–25 wt%) improves mechanical properties and brightness decay resistance	Long-term performance and broader application in road self-illumination
91	Rivera et al., 2021	Characterization and comparison of regular polymer-modified and HiMA asphalt, aging tests	HiMA asphalt shows enhanced long-term mechanical performance compared to conventional polymer-modified binders	Performance assessment
92	Nassar et al., 2021	Study of eco-friendly binders using WCO and WP, physical and rheological property analysis	GBA with 40% WCO and 60% WP shows optimal physical and rheological properties	Performance and large-scale implementation
93	Kakar et al., 2021	Blending waste polyethylene with conventional asphalt binder; DSC, TGA, FTIR, ESEM, and DSR tests	Waste PE improves high-temperature performance and rutting resistance; low-temperature modulus comparable	High-temperature storage stability needs attention
94	Ciaburro et al., 2021	Experimental investigation on sound-absorbing asphalts; numerical simulation using ANN	Neural network model accurately predicts sound absorption coefficient	Field validation and application studies
95	Chompoorat et al., 2021	Experimental stabilization of dredged sediment with OPC and FA	Optimal FA content improves strength and stiffness of stabilized sediments	Empirical correlations for design parameters need further validation
96	Ru Chen et al., 2021	Development and testing of flame-retarded warm-mix epoxy asphalt binders	Improved fire retardancy, lower viscosity, increased T _g , and better thermal stability with RPFR	Slight decrease in break elongation with RPFR inclusion

Table 4. *Cont.*

S/No	Study	Focus	Key Findings	Research Gaps
97	J. Chen et al., 2021	Comprehensive literature review of pavement engineering research	Summarized innovations in materials, performance modeling, multi-scale mechanics, and sustainable and intelligent pavements	Need for further research on integrating new technologies into practical applications
98	Birgin, D’alessandro et al., 2021	Development of a piezoresistive composite pavement material for WIM systems	New composite material shows promising sensing capabilities for traffic detection and WIM	Need for field validation and real-world implementation
99	Bevacqua et al., 2021	Non-destructive rehabilitation method using selective heating for self-healing asphalt	Deep, selective, adaptive, and non-invasive healing of asphalt pavements through electromagnetic fields	Need for further field validation and real-world application studies
100	Autili et al., 2021	Development of a choreography-based service composition platform for UTC application	Successful use of CHOReVOLUTION IDRE for eco-driving services; improved transport performance	Evaluation of long-term benefits
101	Adesina John et al., 2021	On-site qualitative interviews and GIS analysis for sustainable mobility strategies in Lagos	Eco-mobility strategies reduce transportation impacts, improve commuter safety and comfort	Policy framework implementation and long-term evaluation
102	Terrones-saeta et al., 2020	Use of industrial waste materials	Optimal combination of materials improves mechanical properties; sustainable and porous asphalt mixture developed	Broader field application and long-term performance studies
103	Slebi-Acevedo et al., 2020	OGFCs reinforced with nylon and polypropylene fibers; DOE and multi-objective optimization	Nylon fibers improve abrasion resistance; the best design involves nylon fibers, 4.80% binder content, 0.06% fiber content	Need for broader implementation and field validation
104	Si et al., 2020	FEM analysis of asphalt pavement with and without PCM	PCM shows potential for thermal regulation; LHATV and LHAI effective indices	Large-scale application and long-term effects of PCM in pavement
105	Shao and Khreishah, 2020	Vehicle positioning system with photodiodes, LCD shutter, triangulation, and dead reckoning	Achieves sub-meter level location accuracy for lane-level and in-lane positioning	Further validation needed in diverse environments and conditions
106	Shah et al., 2020	Compaction energy methods, ANN analysis with alum sludge as soil stabilizer	8% alum sludge improves soil strength at low compaction energy (600KN-m/m ³)	Needs further field trials to validate laboratory findings
107	Rodríguez-Fernández et al., 2020	Mechanical tests, LCA, and LCCA for sustainable porous asphalt mixtures	Sustainable mixes reduce environmental and economic impacts by 12–15%	Long-term performance and broader applicability needed
108	Peduto et al., 2020	Multi-source data-driven method, DInSAR, and geotechnical modeling	Forecasting settlement scenarios supports informed maintenance decisions	Needs real-world application and validation

Table 4. *Cont.*

S/No	Study	Focus	Key Findings	Research Gaps
109	Olayode et al., 2020	ANN for traffic volume reduction in mixed traffic conditions	ANN model effectively reduces traffic congestion	Requires further validation in different traffic conditions
110	Ogando-Martínez et al., 2020	Model calibration, Radiance and GenOpt algorithm	Achieves 13% error in illuminance and luminance calculations	Further validation in diverse urban environments needed
111	Nowoświat et al., 2020	Testing of thin emulsion mat micro surfacing on SMA, CPX	Micro surfacing reduces noise exposure by 30 m during the day and 50 m at night	Needs long-term studies to confirm durability and performance
112	Mirzananadi et al., 2020	Hybrid 3D and 2D numerical simulations for HHP system	HHP system is effective for anti-icing and solar energy harvesting	Needs field trials to validate simulation results
113	Maduekwe et al., 2020	LEAP model for ASI policy measures in Lagos	ASI measures can significantly reduce emissions if vehicle age and growth rates are controlled	Needs policy implementation and monitoring for real-world impact
114	Foteinis et al., 2020	Industrial-scale LCA of second-generation biodiesel	Biodiesel from used cooking oil has lower environmental footprint compared to petrol and diesel	Needs optimization of collection and processing logistics
115	Ciampa et al., 2020	Study of CDW and EAF slag mixtures for road construction	CDW mixtures show good mechanical properties and environmental sustainability	Needs further testing and validation in large-scale applications
116	Chevalier and Charlemagne, 2020	Survey and analysis of children 's transportation safety in Shanghai	Simple infrastructure improvements can enhance safety and comfort for children	Broader application and validation of proposed solutions
117	Vuong et al., 2019	ARDL and NARDL on 50 years' time series data	Road construction reduces falling dust and CO, increases NO2 and O-x emissions	Exploration of green policies' effectiveness on different pollutants
118	Sutandi et al., 2019	ICT application evaluation, cross-tabulation analysis	ICT improves bus service response, but punctuality and schedule adherence need improvement	ICT implementation is in early stages
119	Z. Sun et al., 2019	Statistical models, experiments on winter temperature extremes	Weibull and Frechet models fit air temperature data; low-temperature properties of asphalt quantified	Limited to Harbin; needs broader geographic validation
120	D. Sun et al., 2019	City-level data analysis (2003–2015)	Roads reduce pollution when eco-industrial parks are nearby; spurs green innovation	Mechanisms behind road impact on pollution
121	Steyn and Maina, 2019	Accelerated pavement testing (APT)	AVs may lead to different pavement behaviors; guidelines for AV-related APT developed	More APT focused on AV operations
122	Priyanka et al., 2019	Laboratory tests on Superpave mixtures	Proposed mixtures for perpetual pavement show improved fatigue and rutting resistance	Requires field validation of laboratory findings
123	Moody et al., 2019	Mixed-method study: time-series clustering, qualitative policy profiling	Identifies four city clusters with distinct urbanization/motorization and policy trends	Further research needed to validate findings

Table 4. *Cont.*

S/No	Study	Focus	Key Findings	Research Gaps
124	Jullien et al., 2019	Ecotoxicity/toxicity assessment of granular materials	Significant differences in environmental impact favoring recycled materials	Needs long-term field validation of lab results
125	Hu et al., 2019	Special Volume (SV) of JCPL on sustainability in transportation	Reviewed themes on sustainability from 10th ICPT conference and JCPL submissions	Broad thematic scope and focus on specific sustainable practices
126	Gallelli et al., 2019	VISSIM simulation, genetic algorithm for calibration	Enhanced correlation between observed and simulated traffic conflicts	Simulation fails in unusual driving behavior scenarios.
127	Dwaikat, 2019	Integrative planning approach, SWOT analysis	Proposes strategies for sustainable transportation in developing countries	Needs practical implementation and real-world testing
128	Covarrubias et al., 2019	Rheological-mechanical properties analysis of WMA	Greasy diamide in WMA improves properties while reducing temperature and compaction energy	Needs long-term performance data to confirm findings
129	Chen et al., 2019	LCCA for pavement rehabilitation strategies	SS-PAC shown to be cost-effective over 40-year period	Field performance data
130	Caro et al., 2019	Cement stabilization impact on lateritic soils	Cement stabilization improves mechanical properties for low- to medium-volume roads	Further research needed on long-term durability
131	Amin et al., 2019	GEOPHRIV index, linear programming for M&R	Optimized M&R strategy ensures good road condition with minimal budget	Needs broader geographic application and validation
132	Aamir et al., 2019	CBR test, ANN for alum sludge soil stabilization	Alum sludge significantly improves soil strength at 8% addition	Validation needed to confirm lab results
133	Vaezipour et al., 2018	Simulated driving experiment with 40 drivers	Combined advice and feedback system reduced fuel consumption and improved eco-safe driving	Systems with feedback increased driver workload
134	Tattini et al., 2018	MoCho-TIMES methodology applied to Denmark 's transport sector	Modal shift towards transit and non-motorized modes can decarbonize the transportation sector	Requires extensive data and mathematical expressions for accurate modeling
135	Schacht et al., 2018	Development of a multi-layered wearing course system	New surface material concept reduced tire-road noise by more than 8 dB(A)	Study of marketable product and structural feasibility analysis
136	Rigot-Müller, 2018	Analysis of France 's écotaxe implementation	Identified reasons for écotaxe failure, including perceived inequities and ad valorem surcharging issues	Retrospective analysis: findings need application in future ETS planning
137	Moreno-Navarro et al., 2018	Rheological and thermal tests on graphene-modified binders	Graphene improved elasticity and reduced thermal susceptibility of asphalt binders	Recovery capacity not as effective as other modifiers like elastomers
138	Mishra and Kumar Gupta, 2018	Experiments on clayey soil with recycled PET fibers and fly ash	Improved shear strength, CBR value, and decreased plasticity index with 1.2% PET and 15% fly ash	Requires field validation for long-term performance

Table 4. *Cont.*

S/No	Study	Focus	Key Findings	Research Gaps
139	Mirzananamadi et al., 2018	Hybrid 3D numerical model for anti-icing with HHP system	Optimal required energy for anti-icing calculated as 106.6 kWh/ (m2 year)	Limited to Östersund; broader climatic data needed
140	Jerez et al., 2018	Characterization of lateritic soil with organosilane	Stabilized soil achieved 533% higher soaked CBR values	Geographic validation needed
141	Gusty et al., 2018	Laboratory testing of Buton Granular Asphalt (BGA)	BGA in porous asphalt showed good stability and tensile strength	Technical constraints in remote areas without asphalt mixing plant
142	Gáspár and Bencze, 2018	DURABROADS project, European-wide survey	Optimized asphalt mixtures with slags, RAP, WMA additive, and nanotechnology showed no negative influence on properties	Needs detailed procedures for production and utilization
143	Vleugel and Bal, 2017	Analysis of urban transport with autonomous cars	Proposed replacement of private cars with shared electric self-driving cars	Needs practical application and policy implementation
144	Vaitkus et al., 2017	Research on low-noise asphalt mixtures for Lithuanian climate	Developed efficient low-noise pavement solutions; positive lab results	Under real traffic and climate conditions
145	Tsita and Pilavachi, 2017	LEAP modeling for Greek road transport decarbonization	Increased penetration of biofuels, electric vehicles, and gas engine vehicles reduced energy consumption and CO ₂ emissions	High uncertainty in selecting specific options for 2050
146	Stryk et al., 2017	GPR measurements for pavement diagnostics	Recommendations for performing and evaluating in situ GPR measurements	Needs further comparative measurement and accuracy analysis
147	Setyawan et al., 2017	Laboratory experiment on open-graded asphalt with natural and volcanic gravel	Found optimal bitumen content and improved mechanical properties for both gravels	Compatible only with low volume traffic; needs improvement for standard roads
148	Ramalingam et al., 2017	Laboratory tests on bituminous mixes with sisal fibers	Optimal performance with 15 mm fiber length at 0.05% dosage, improving stiffness modulus, fatigue life, and moisture sensitivity	Further field validation required for diverse environmental conditions
149	Pereira and Pais, 2017	Historical overview and comparison of pavement design methods	Highlighted limitations of empirical methods; presented French, UK, and Shell methods and their challenges	Need for updated and harmonized European pavement design method
150	Lastra-González et al., 2017	Design and characterization of PA mixture with EAF slag and CRM binder	Wax addition decreased manufacturing temperature and improved bitumen modulus without significant mechanical impact	Long-term performance and environmental impact studies needed
151	Kambole et al., 2017	Evaluation of BOF slag in bitumen mixes	Better resilient moduli, rutting, and moisture resistance than natural aggregates; concerns about free lime and heavy metals	Assessment and monitoring of environmental impacts required

Table 4. *Cont.*

S/No	Study	Focus	Key Findings	Research Gaps
152	Chomicz-Kowalska and Ramiączek, 2017	Comparison of compaction methods for recycled mixtures	Hydraulic press method produced over-compacted samples with better strength and water resistance	Calibration of compaction methodology needed for realistic field conditions
153	Chen et al., 2017	Experimental and model analysis of dielectric loss in IPT technology	Dielectric loss effect impacts power transfer efficiency in electrified roads	Prioritization of future research on materials with lower dielectric loss
154	Balasubramaniam et al., 2017	Analysis of sustainable IoV systems	Recommendations for sustainable transportation planning integrating pollution-free systems and road safety	Need for practical implementation and testing of proposed systems
155	Yalçiner Ercoşkun, 2016	Exploration of GIS and ICT in public transport	Positive impact of mobile technology and social media on sustainable mobility and community engagement	Challenges in implementation for disadvantaged groups
156	Tabaković et al., 2016	Development of cold recycling specifications and case study in Ireland	Effective rural road rehabilitation with significant CO ₂ and cost reductions	Challenges in curing and testing protocols in colder climates
157	Setyawan et al., 2016	Laboratory tests on open-graded asphalt with natural and volcanic gravel	Higher permeability and strength for volcanic gravel; suitable for low volume traffic	Improvements needed for use on standard roads
158	Sangiorgi et al., 2016	Evaluation of waste bleaching clay as filler in PA mixture	Improved ITs, stiffness, and deformation resistance with waste clay compared to traditional filler	Long-term durability and field performance studies needed
159	Noh and Baek, 2016	Development of green highway certification and technologies in Korea	Proposed green highway design, construction, and carbon management system	Requires broader implementation and validation
160	Köse et al., 2016	Exploration of overcompliance in sustainable manufacturing	Identified competitive advantages in overcompliance with emission standards	Consistent regulatory frameworks
161	Hernández González and Corral Quintana, 2016	Participatory approach to transport governance in Tenerife	Identified policy issues and alternatives with stakeholder involvement; validated results through stakeholder discussion	Challenges in achieving consensus and effective policy implementation
162	Gáspár et al., 2016	Quantification methodology, surveys, and decision support model (AHP, TOPSIS)	Identified Stone Mastic Asphalt (SMA) as suitable for different climates	Need for validation through real-world applications
163	Bastos et al., 2016	Chemical, mineralogical, physical characterization, stabilization tests	Iron ore tailings are feasible for road paving when stabilized with cement	Further research required for slag-tailing durability
164	Yang et al., 2015	Development and integration of wireless communication in SHMM	Reliable wireless communication for pavement monitoring over 46 m distance	Further field validation needed for diverse conditions
165	Setyawan et al., 2015	PCI method, vehicle speed and emissions calculations	Poor road conditions decrease vehicle speed by 55%, increase emissions by 2.49%	Conditions to reduce emissions and improve safety

Table 4. *Cont.*

S/No	Study	Focus	Key Findings	Research Gaps
166	Nazarko et al., 2015	Delphi forecasting method	Identified future trends in road construction materials and technologies	Continuous monitoring and adaptation to new technologies
167	Guo et al., 2015	Development of EcoSky system, GPS data analysis	Provided eco-friendly routing options considering fuel consumption, travel time, distance	Personalization of routes based on driver behavior
168	Chrysochoidis-Antsos et al., 2015	GIS data, assessment of wind turbine feasibility	Wind turbines along highways could produce enough hydrogen for fuel cell cars	Implementation and integration with existing infrastructure needed
169	Trojanová, 2014	Proposition of asset management recommendations	Effective asset management crucial for road maintenance in Slovakia	Implementation and adaptation to new market conditions required
170	Timm and Tran, 2014	Life cycle cost analysis, field performance evaluation	Perpetual pavements showed 26% savings compared to non-perpetual pavements	Need for long-term performance data and broader implementation
171	Timm et al., 2014	Full-scale pavement test sections, strain measurements	Perpetual pavements demonstrated excellent performance over 30 million loads	Further analysis on aging without damage needed
172	Schweikert et al., 2014	Software tool analysis, climate change scenarios	Proactive adaptation reduces fiscal costs and increases connectivity	Adaptation for low-income countries
173	Ferrotti et al., 2014	Experimental characterization of cold mix asphalt with fibers	Cellulose fiber-reinforced mix showed better performance and curing times	Comparison with other cold mix asphalt products needed
174	Dondi et al., 2014	Analysis of cold recycled mixes with crumb rubber	Evaluated physical and mechanical characteristics of crumb rubber in mixes	Optimal mix designs for various conditions
175	Castillo and Caro, 2014	Probabilistic theory, finite element modeling, simulation techniques	Spatial variability provides better insight into structural reliability of pavements	Need for validation in real-world conditions

The included articles on eco-friendly road infrastructure for sustainable transportation, spanning a wide range of research areas, are discussed in the following sections: sustainable materials, renewable energy integration, policy and regulation, life cycle assessment (LCA) and management, AI and machine learning (ML), environmental impact and mitigation, Intelligent Transportation Systems (ITs), pavement performance evaluation, and waste utilization and recycling.

4. Eco-Friendly Road Infrastructure in the Context of Sustainable Transportation Research Areas

4.1. Sustainable Practices in Road Infrastructure

4.1.1. Sustainable Materials

Research on sustainable materials has explored areas such as natural fiber reinforcement, nanotechnology in asphalt mixtures, geopolymers and advanced composites, and bio-based solutions. Additional areas cited in the literature include waste by-product stabilization, industrial waste utilization, and conductive additives. These studies collectively underscore the potential of waste materials in sustainable road infrastructure while highlighting gaps requiring further investigation. Natural fiber reinforcement has been cited in the literature as being used for improvements in density, compressive strength, shear strength, and CBR of road pavement using citric acid-treated natural fibers in soil [42]. Improvements have also been reported in bituminous mixes enhanced with sisal fibers, with findings that show improved stiffness modulus, fatigue life, and moisture sensitivity, achieving optimal performance with 15 mm fiber length at 0.05% dosage [43]. Despite the promising results, there has been limited evidence of field studies carried out under diverse environmental conditions to fully understand the long-term benefits and practical applicability of natural fiber reinforcement in road construction. Figure 4 shows the main types of natural fiber reinforcement materials and properties and the naturally occurring sources with pictures.

NATURAL FIBER REINFORCEMENT MATERIALS AND PROPERTIES							
	Jute Fiber	Coconut Coir Fiber	Bamboo Fiber	Hemp Fiber	Flax Fiber	Sisal Fiber	Kenaf Fiber
SOURCE							
PROPERTIES	High tensile strength, biodegradable, cost-effective	Good insulation properties, biodegradable, abundant availability	High strength-to-weight ratio, fast-growing renewable resource, biodegradable	High tensile strength, renewable, biodegradable	High stiffness and strength, biodegradable, low density	High durability, biodegradable, resistant to rotting	High tensile strength, biodegradable, fast-growing crop
FIBRE							

Figure 4. Natural fiber-reinforcement materials and properties for eco-friendly road construction.

Like natural fiber reinforcement, nanotechnology in asphalt mixtures has been studied for decades, but it has recently experienced a resurgence due to significant advancements in the knowledge of properties and performance of road materials [44]. The literature suggests that incorporating nanoparticles like nano-clay, nano-silica, and nanotubes into asphalt binders could increase viscosity, which, in turn, improves fatigue resistance. Nano-clay, for instance, when used as a secondary modifier in polymer-modified asphalts, has been shown to have potential to enhance storage stability and aging resistance [45]. Techniques like Atomic Force Microscopy (AFM) and X-ray diffraction (XRD) have been applied in studies to characterize the micro- and nano-scale structures of modified asphalts [46]. The

results have suggested that nanomaterials, such as aluminum oxide (Al_2O_3) and nano-silica, significantly improve the resistance to fatigue and moisture susceptibility, and reduce permanent deformation, leading to improved durability and extended service life of pavements. Despite these benefits, further research is required to understand additional benefits and characteristics of nanomaterials, especially as it relates to integration with asphalt for practical implementation to address eco-friendly road infrastructure challenges [45]. Table 5 shows the main types of nanomaterials cited in the reviewed literature and the usage with sources.

Table 5. Nanomaterials and applications in eco-friendly road infrastructure as cited in the literature.

Nanomaterial	Description of Use	Citations/Sources
Nano-clay	Improves mechanical properties	[47,48]
Nano-silica	Improve mechanical performance	[49,50]
Carbon nanotubes (CNTs)	Reinforces asphalt mixtures	[51,52]
Nano-titanium dioxide (TiO_2)	Provides photocatalytic properties	[45]
Nano-alumina	Enhances performance	[45]
Nano-iron oxide	Modifies asphalt mixtures for better performance	[45,50]
Nano-calcium carbonate (CaCO_3)	Improves properties	[50,53]
Nano-graphene	Modifies asphalt mixtures	[32,54,55]

Other sustainable materials such as geopolymers and advanced composites offer promising solutions for sustainable road infrastructure [56]. They are materials mainly derived from industrial by-products and waste, such as fly ash and slag, and in road infrastructure research they are seen as viable eco-friendly alternatives to Portland cement [57]. The reuse of industrial by-products for soil stabilization, as cited in the literature, demonstrates the potential of geopolymers to enhance soil properties and durability [58]. Similarly, the mechanical properties and self-healing capabilities of geopolymer-reinforced composites have been demonstrated, which could have significant benefits if well harnessed [59]. Innovations in geopolymers have the potential to have significant environmental benefits as shown in Table 6 below. Future research should consider issues of scalability, and the development of standardized guidelines for their widespread adoption in road construction.

Table 6. Geopolymers and advanced composites and applications in eco-friendly road infrastructure as cited in the literature.

Material	Description	Areas of Use	Citations
Fly ash-based geopolymers	Fly ash and alkaline activators	Used as a binder in pavement construction	[50,60–62]
Metakaolin-based geopolymers	Calcined kaolinite clay and alkaline solutions	Soil stabilizing agent	[63]
Slag-based geopolymers	Ground granulated blast furnace slag and alkaline solutions	Road base layers	[46,50,56,64–67]
Glass-fiber-reinforced polymer (GFRP)	Polymer matrix reinforced with glass fibers	Bridge decks, guardrails, and asphalt reinforcement	[68]
Carbon-fiber-reinforced polymer (CFRP)	Polymer matrix reinforced with carbon fibers	Bridge strengthening, pavement reinforcement	[50]
Basalt-fiber-reinforced polymer (BFRP)	Polymer matrix reinforced with basalt fibers	Road pavement reinforcement, alternative to steel	[69]

Similarly, bio-based asphalt solutions have been cited as being adopted with significant interest by countries committed to reducing their carbon footprint and enhancing

the sustainability of their infrastructure [70]. Reviewed literature on bio-based thermo-sensitive NaCl brine developed for anti-icing showed potential for improving efficiency in maintenance of pavement [71]. Other studies have shown the potential of citric acid use in treating natural fibers, like sawdust, for enhancement of soil properties [42]. Figure 5 below highlights the bio-based materials and their common areas of application in the cited literature.

BIO-BASED MATERIALS AND AREAS OF APPLICATION							
	Trees	Soybeans	Tree, shrubs and leaves	Corn-Based Polylactic Acid (PLA)	Algae-Based	Natural Rubber	Recycled Vegetable Oils
SOURCE							
PRODUCTS	Lignin-Based Binders	Soybean Oil-based Polyurethane	Bio-Char	Corn-Based Polylactic Acid (PLA)	Algae-Based Binders	Natural Rubber	Recycled Vegetable Oils
EXAMPLES OF AREA OF APPLICATION	Partial replacement for bitumen in asphalt	Road paving, sealant for pavement preservation	Modifier in asphalt mixtures	Erosion control mats, soil stabilization, drainage systems	Road paving, modifier for asphalt mixtures	Rubberized asphalt for road paving and maintenance	Asphalt rejuvenation and modification

Figure 5. Bio-based materials and areas of application.

Research on sustainable materials for road infrastructure reveals significant advancements in areas such as natural fiber reinforcement, nanotechnology in asphalt mixtures, geopolymers, advanced composites, and bio-based solutions. These studies highlight the potential of these materials to enhance eco-friendly road infrastructure but also identify gaps needing further exploration. For instance, natural fibers have shown improvements in pavement properties, yet field studies under varied conditions are scarce. Nanotechnology has advanced the understanding of asphalt properties and enhanced durability but requires more research for practical use. Geopolymers and advanced composites offer eco-friendly alternatives to traditional materials, though scalability and standardization are needed. Bio-based solutions also show promise in reducing carbon footprints and improving maintenance. Overall, while progress is evident, ongoing research and field validation are essential to fully realize the benefits of these sustainable innovations.

4.1.2. Eco-Friendly Asphalt Pavement and Construction Technology

Research into cutting-edge asphalt pavement and construction techniques, focused on minimizing carbon emissions and improving the longevity of road infrastructure, has highlighted innovations like Recycled Asphalt Pavement (RAP), Warm Mix Asphalt (WMA), and perpetual pavement. These advancements, as documented in the literature, demonstrate significant potential for enhancing both environmental sustainability and economic efficiency in road construction [72]. Studies, including those by Wang and Dong [73], Karthikeyan, Kothandaraman [74], and Polo-Mendoza, Peñabaena-Niebles [75], highlight RAP's positive impact on workability, mechanical properties, and durability of asphalt mixtures. Some researchers have integrated RAP with other technologies such as RAP-HMA involving hot RAP feeding and rejuvenator addition for better mix design [76]. Despite all the progress, challenges such as the need for comprehensive evaluation of innovative materials, careful adjustment of design conditions, and the enhancement of RAP concrete strength have been cited [74,76]. Based on laboratory test results and case studies, there remains ongoing interest in identifying areas of application and continually optimizing these methods to enhance sustainability gains. Figure 6 below highlights the types of RAP and processes in cited literature.

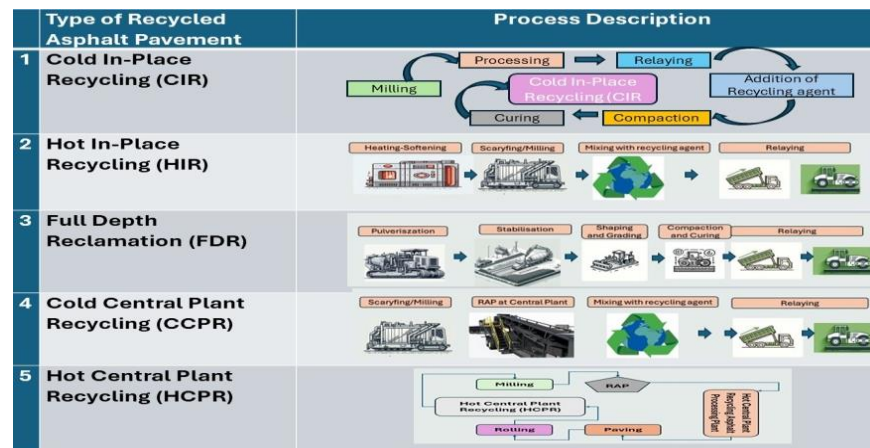


Figure 6. Types of Recycled Asphalt Pavement (RAP) and processes as cited in the literature.

Warm Mix Asphalt (WMA) technology, developed in the late 1990s primarily to allow production of asphalt at lower temperatures, has over the years evolved to include introduction of additives and development of WMA standards and specifications promoting its widespread use [77]. Studies such as that by Polo-Mendoza, Mora [78] and Covilla-Varela, Turbay [49] sought to integrate WMA with recycled materials like Recycled Concrete Aggregate (RCA) and Recycled Asphalt Pavement (RAP), further improving sustainability and mechanical performance. The evolution of the concept will require continuous improvement in design conditions, validation of long-term performance, and review of standardized guidelines to improve adoption for sustainable transportation around the world. Figure 7 below shows the typical process diagram for a WMA.

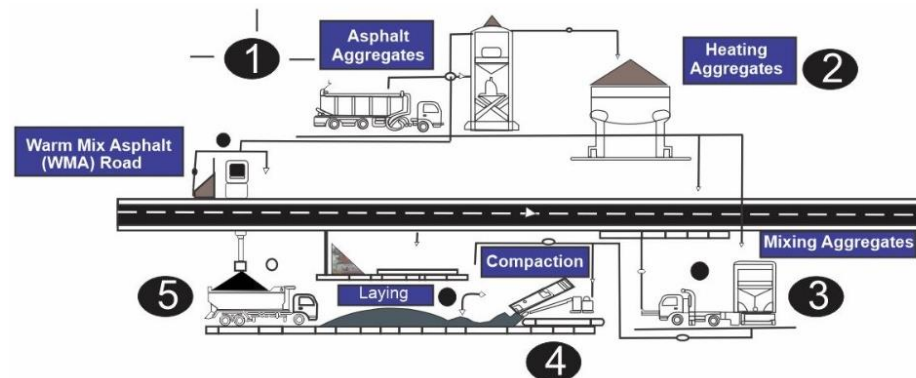


Figure 7. Warm Mix Asphalt (WMA) process diagram (75).

Apart from WMA, perpetual pavements, which are asphalt pavements engineered to last indefinitely via their layered design, have shown potential to prevent deep structural damage resulting in economic and environmental benefits [79]. Studies such as that by Polo-Mendoza, Mora [78] have highlighted the potential environmental and economic benefits over conventional flexible and rigid pavements. Using the life cycle assessment (LCA) tool, the life cycle cost analysis (LCCA) suggested that perpetual pavements offer less environmental damage and higher cost-efficiency [78]. Earlier studies, such as that from Timm and Tran [80], Timm, Robbins [81] carried out on the National Centre for Asphalt Technology (NCAT) Pavement Test Track, suggested that perpetual pavement results in LCCA savings of 26% when compared to traditional pavement types. Despite the research interest, there has been little evidence of application of perpetual pavement in real-life scenarios with long-term performance in diverse climatic and traffic conditions. Figure 8 below shows a typical perpetual pavement construction process.

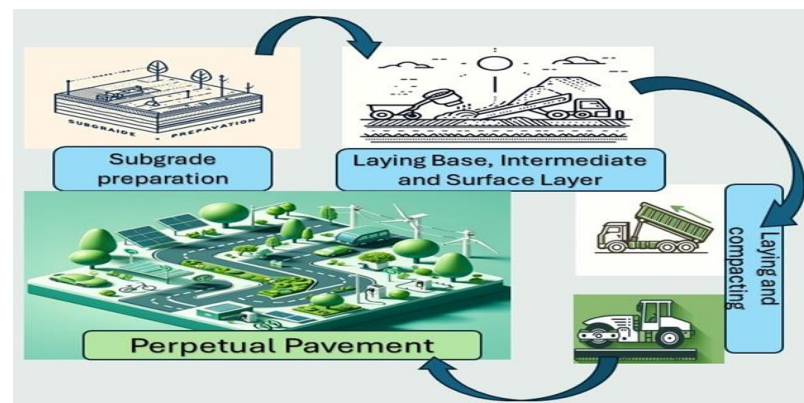


Figure 8. Perpetual Pavement process diagram (76).

Innovations in asphalt pavement construction technology have explored the integration of renewable energy in road transport infrastructure, focusing on solar roadways and photovoltaic pavements, wind turbines integrated into infrastructure, and various energy harvesting technologies. Research into innovative solar pavements, capable of harvesting and converting solar energy into electricity, has resulted in the development of many prototypes with two main methods gaining prominence [82]. In one method a “solar panel” is embedded in rubber and Plexiglas and integrated with the road infrastructure while the second method has a “solar pavement” with solar cells between two porous rubber layers [83]. Research conducted on solar pavement demonstrated a potential higher power conversion efficiency (PCE) of 5.336% compared to the solar panel [84]. A BPT test conducted on the different solar energy pavement types was said to show values in even wet conditions of 42 for the solar panel and 47.8 for the solar pavement [84]. While the prototypes showed promise, further research is needed to address these issues and optimize the materials used in solar pavements. Figure 9 below shows the applications of solar and photovoltaic elements to road infrastructure.

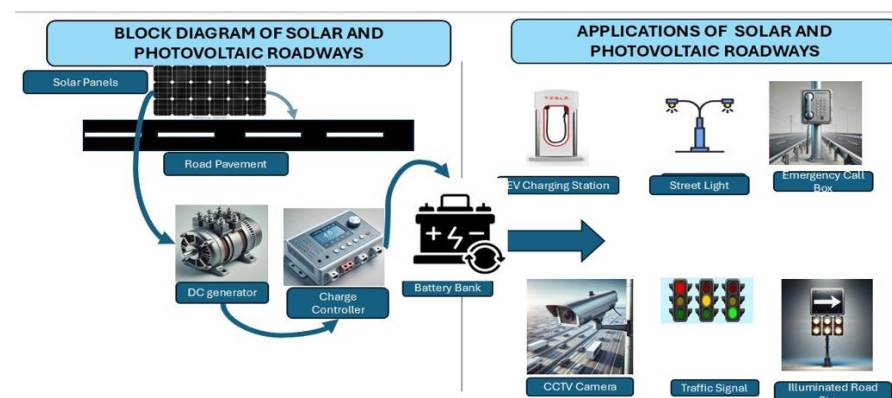


Figure 9. Application of solar and photovoltaic elements to road infrastructure (83).

The exploration of harnessing wind from the side of road networks has long been of interest to researchers, and recent proposals for integrating wind turbines into road infrastructure offer a potentially sustainable solution for generating renewable energy [85]. Researchers have explored installing turbines along highways or within medians to capture wind from passing vehicles and natural flows. This energy can potentially be used to power streetlights, traffic signals, EV charging stations, and contribute to the local power grid, thereby reducing fossil fuel reliance [86]. The literature cites various implementations: vertical axis wind turbines (VAWTs) on highway dividers in Chennai, India [87], medians in the ENLIL project in Istanbul, Turkey [88], and rights-of-way on Norway’s E39 highway [89], all aiming to harness wind from traffic and natural flows to generate renewable

energy. The scalability, cost-effectiveness, and design optimization of the proposals are still a subject of interest. Figure 10 below illustrates a vertical axis wind turbine process with areas of application.

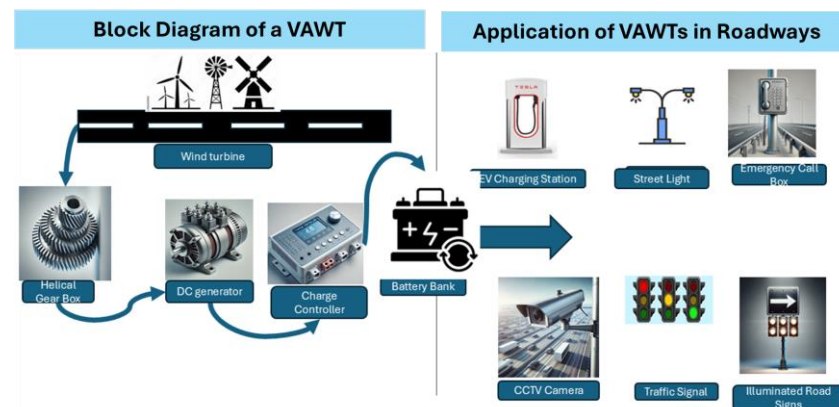


Figure 10. Vertical axis wind turbine (VAWT) integration with road infrastructure (87).

Other cited literature has explored thermal energy harvesting technologies for sustainable road infrastructure with the most promising result achieved utilizing the Seebeck effect, where a temperature difference across thermoelectric materials generates electrical voltage. The method utilizes the heat from road surfaces, created by sunlight and vehicle friction, using thermoelectric generators (TEGs). Experimental studies, such as those conducted in San Antonio, Texas, assert that significant temperature gradients within road depths could enable electricity generation [90]. Other innovative uses of the same concept has been explored with various materials and systems seeking to optimize efficiency and facilitate large-scale, practical applications [91,92]. Figure 11 below highlights the application of road thermoelectric generators in road infrastructure development.

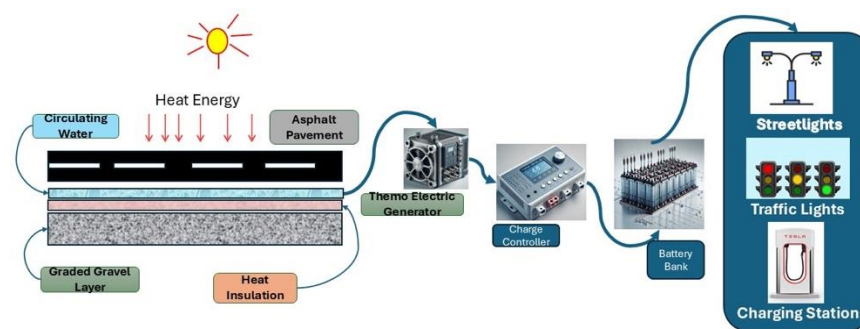


Figure 11. Application of road thermoelectric generator systems (RTEGSs) (88).

Renewal energy integration in road infrastructure research has explored piezoelectric energy harvesting technologies capitalizing on the direct piezoelectric effect, where mechanical vibrations are converted into electrical potential [93] as shown in Figure 12. The cited literature has explored the use of “piezoelectric materials”, which consist of naturally occurring and sometimes synthetic materials such as lead zirconate titanate (PZT) as illustrated in Figure 12 below [94]. Researchers have explored the use of the material in various applications, including cantilever beams, disks, cylinders, and stacks, for their mechanical strength and efficiency under road conditions [95,96]. Studies have shown promising results; bridge piezoelectric harvesters placed between protective caps produced significant voltage outputs under simulated traffic conditions [92,97]. Other studies have designed innovative cymbal transducers and piezoelectric cementitious composites aiming to combine piezoelectric particles with cement, which are being developed to serve both as construction materials and energy harvesters [98]. Research in the subject area is now directed towards

optimizing the output and durability of these systems under real-world conditions to enhance their practicality and efficiency for sustainable road infrastructure [93,94,98].

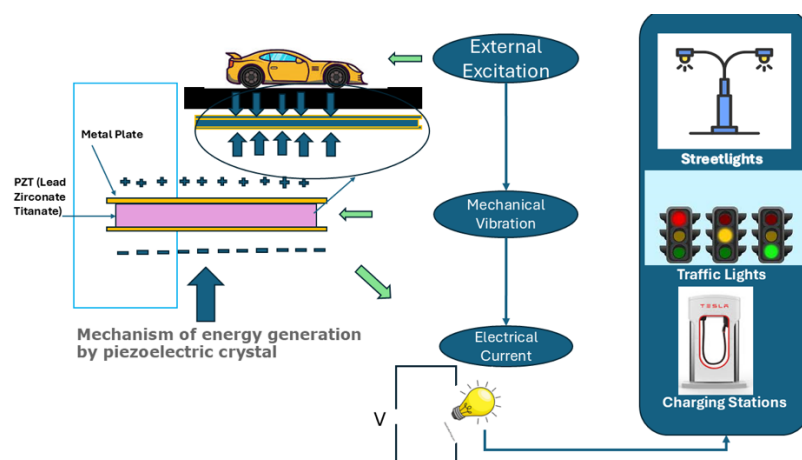


Figure 12. Application of piezoelectric energy harvesting in road infrastructure [93].

Eco-friendly asphalt pavement and construction technology has shown great promise in enhancing environmental sustainability and economic efficiency. Innovations such as Recycled Asphalt Pavement (RAP), Warm Mix Asphalt (WMA), and perpetual pavements reduce carbon emissions and improve road longevity. RAP improves the durability and workability of asphalt mixtures, while WMA allows lower-temperature production, enhancing sustainability when combined with recycled materials. Perpetual pavements offer significant economic and environmental benefits through their long-lasting design. Renewable energy integration, including solar roadways, wind turbines, and thermoelectric generators, presents additional opportunities for sustainable road infrastructure. However, further research and real-world application studies are needed to fully realize these technologies' potential benefits.

4.2. Waste Management and Environmental Impact

Waste utilization and recycling in eco-friendly road infrastructure has been a topic of interest because of the large amount of material required for civil engineering road projects. Research into waste utilization and recycling in road construction has focused on various innovative solutions to enhance sustainability and performance. Some innovative solutions cited in research include incorporating Recycled Asphalt Pavement (RAP) into new mixtures [99], utilizing Recycled Concrete Aggregate (RCA) from demolished structures [78], and adding plastic waste to asphalt mixtures to improve durability [100]. Industrial by-products such as fly ash, slag, and silica fume are being used in concrete and asphalt mixtures to enhance mechanical properties [101]. Apart from industrial by-products, researchers have explored waste from agricultural residues such as biomass ash [102], and even construction and demolition waste [103]. Furthermore, the potential of incorporating electronic waste (e-waste) into road construction is under investigation [104]. These efforts aim to improve sustainability, performance, and cost-effectiveness by reducing environmental footprints and promoting eco-friendly road construction. Eco-friendly road infrastructure research has emphasized the reduction in the carbon footprint, improving air quality, conserving water, and enhancing acoustic insulation for overall environmental impact and mitigation. The cited literature integrates eco-friendly materials and intelligent systems, aiming to support the creation of environments that are quieter, more efficient, and significantly less impactful on the environment. This comprehensive approach supports the development of sustainable transportation solutions that address both current needs and future challenges.

Recent studies have shown progress in understanding the carbon footprint of road infrastructure, and innovative methodologies and advanced technologies have been devel-

oped that have shown potential. A study developed a comprehensive framework utilizing the Gradient Boosting Decision Tree algorithm to assess and predict the carbon footprint of urban road networks [30]. The study claimed to have identified that material production accounts for 78% of total greenhouse emissions in road infrastructure projects. The results suggested that their predictive model achieved high accuracy with a relative error below 2%, facilitating the development of carbon-neutral urban transport systems [30]. Similarly, a study demonstrated that optimizing inverted pavements reduces carbon footprint during the operation phase [101]. Other studies have used long-term monitoring data and advanced deep learning models, such as Temporal Convolution Networks (TCNs), optimization of Warm Mix Asphalt (WMA) with Recycled Concrete Aggregate (RCA) [78], self-sustainable weigh-in-motion (WIM) technology using smart pavements and vibration-based energy harvesting, and so on to reduce environmental impacts through reduction in carbon footprint of road infrastructure [93]. Studies into integration of AI and IoT technologies, such as the IoT system for monitoring pavement vibrations, further contribute to carbon footprint reduction by enhancing maintenance efficiency and reducing repair frequency. These studies collectively underscore the pivotal role of integrating advanced technologies and sustainable materials in achieving substantial carbon footprint reductions in road infrastructure.

The cited literature seeking to improve air quality through innovative road infrastructure enhancements have leveraged the use of eco-friendly materials, technological advancement, and methods for improvements [11]. In a study in China, integration of road infrastructure with green elements was shown to result in a significant reduction in air pollution [105]. The study analyzed data from 2003 to 2015 and claimed that green features could significantly improve road environmental performance, especially when near eco-industrial parks. The research highlighted the crucial role of well-planned transportation infrastructure in advancing air quality and sustainable development. Also, efficient management of traffic flow through a careful vehicle positioning system has been shown to impact air quality [106]. To that end, studies have sought the integration of Intelligent Transportation Systems to not only enhance traffic management and reduce congestion, but also to improve air quality [100,107,108]. Other studies have concentrated on the development of performance indicators for sustainable transportation with air quality identified as a key parameter [109]. Collectively, these studies underscore the importance of integrating technologies, techniques, and management tools to enhance air quality improvements through road infrastructure enhancements.

Eco-friendly road infrastructure research has explored water conservation to advance the development and implementation of strategies and technologies to decrease water usage and manage stormwater effectively [110]. New innovative methods cited in the literature have included permeable pavements, which reduce runoff and promote groundwater recharge [29,111,112] and green highways that integrate vegetation to manage stormwater [110]. Other technologies cited involved utilization of UAV-based inspections and fiber-optic sensor technologies to enhance efficiency in the maintenance and management of water [113]. These studies collectively underscore the critical role of advanced technologies and sustainable materials in promoting water conservation within road infrastructure projects. Other environmental impacts explored in the cited literature include acoustic insulation.

Research into acoustic insulation in eco-friendly road infrastructure research has mainly been aimed at reduction in noise pollution through the development of innovative materials and designs to enhance insulation properties of pavement and/or the mitigation of the effects in the environment [114]. A study investigated sound-absorbing asphalts for urban areas, showing that these materials significantly reduce noise emissions. The research includes experimental measurements of sound absorption coefficients and the development of a neural network model for accurate predictions [115]. Noise pollution reduction has been cited as a key benefit that can potentially be derived from improved traffic

management and quieter road surfaces using technologies like Intelligent Transportation Systems (ITs) [100].

In conclusion, eco-friendly road infrastructure research emphasizes using recycled materials, such as RAP, RCA, plastic waste, and industrial by-products, to enhance durability and sustainability. Efforts focus on reducing carbon emissions, improving air quality, conserving water, and enhancing acoustic insulation. Advanced technologies like AI and IoT optimize materials, predict environmental impacts, and improve maintenance efficiency. These innovations collectively highlight the importance of integrating sustainable materials and cutting-edge technologies to create environmentally friendly and efficient road infrastructure.

4.3. Evaluation and Management

Research into LCA and management has investigated the carbon emissions arising from road pavement infrastructures from raw material extraction, production, construction, use, and maintenance up to end of life. A review of 126 articles related to carbon emission quantification, influential factors, and reduction technologies conducted by Zhu, Li [29] asserted that the LCA approach is the most widely used evaluation method for carbon emission impacts and that the most significant factors relating to pavement use are pavement–vehicle interaction, which is primarily affected by pavement roughness, pavement albedo, and climate change. Challenges associated with LCA were identified by Babashamsi, Md Yusoff [116], who asserted that existing LCCA methods and software need to be improved to facilitate wider application.

LCA has been cited in numerous studies as a tool for comparison of different pavement types to determine the most efficient in terms of carbon footprint. Researchers carried out life cycle cost analysis and life cycle assessment of inverted pavement with an optimized pavement cross-section to ascertain the carbon footprint during the vehicle operation phase [101]. Other studies used assertion of lower LCC to advocate for adoption of semi-rigid base asphalt pavement designed with interlayers with potential to delay and prevent crack propagation effectively, reducing crack-related distress significantly [117]. LCA has been cited to have been used to justify the use of other more eco-friendly materials such as lignin [118], porous asphalt mixtures [119], and so on. LCA research has also included LCA in multi-criteria assessment of key performance indicators for sustainable transportation. Bhattacharya, Sarkar [109] used factor analysis and structural equation modeling (SEM) to analyze sustainable practices and their interdependencies, guiding the development of resilient infrastructure.

4.4. Policy, Regulation, and Advanced Technologies

Policies and regulations for sustainable road development are multifaceted, encompassing legislative frameworks, environmental and economic policies, social regulations, safety standards, and implementation strategies. These elements work together to promote eco-friendly road infrastructure, reduce environmental impact, and ensure community involvement, ultimately contributing to a more sustainable and resilient transport system. A key area in terms of policy and regulation is the legislative framework for sustainable road development, which involves national and international laws that govern road construction and maintenance, ensuring they adhere to eco-friendly standards. Key regulatory bodies, such as environmental agencies and transport departments, play critical roles in enforcing these regulations and promoting sustainability [85].

Another important aspect is environmental regulations, which are fundamental in mitigating the ecological impact of road infrastructure. Standards for environmental impact assessments (EIAs) ensure comprehensive evaluations of potential environmental damage [120]. Policies focus on reducing carbon emissions, protecting biodiversity, and conserving natural habitats. These measures are crucial as road freight transportation significantly contributes to global CO₂ emissions, necessitating strategic solutions like route optimization to minimize environmental externalities [11,87]. Research has asserted

that environmental factors are key drivers in the deployment policy recommendations on sustainable transportation [121].

Research has found that economic policies underpin sustainable road projects through funding and financing strategies, such as public–private partnerships and green bonds. Incentives for using sustainable materials and technologies, like thermoelectric generators and piezoelectric harvesters, encourage their adoption. Cost–benefit analyses compare the long-term benefits of sustainable road development against traditional methods, emphasizing economic and environmental advantages [84].

Similarly, social regulations in road infrastructure development ensure community engagement by mandating public participation and stakeholder involvement, addressing social impacts and enhancing project acceptance. Modal shift measures are essential for promoting eco-friendly transport modes and reducing the negative impact of road freight, with eleven measures identified to improve intermodal services and infrastructure, supporting carbon neutrality goals [86]. Route optimization using a GIS-based 3D-Routing Model can reduce emissions by estimating vehicle fuel consumption, though it may increase operational costs [89]. In Krasnodar, Russia, developing eco-friendly tourism policies and promoting eco-labeling can help maintain ecosystem quality amidst increasing tourist flows, with public awareness and willingness to pay for such services being crucial [122].

4.5. AI, Machine Learning, and Intelligent Transportation Systems (ITSs) in Road Infrastructure

The integration of artificial intelligence (AI), machine learning (ML), and Intelligent Transportation Systems (ITS) has marked significant advancements in the quest for eco-friendly road infrastructure. Research has highlighted the contributions of ITSs in enhancing eco-friendly road transport through advanced traffic management, real-time traveler information, optimized public transit, and cooperative autonomous vehicles. Leveraging technologies such as information and communication technology (ICT), Global Positioning System (GPS), Light Detection and Ranging (LiDAR), and AI, studies have demonstrated the potential of these systems to reduce congestion, improve navigation, and minimize environmental impact, thereby promoting sustainable transportation.

Research in ITs has emphasized the application of advanced technologies to enhance efficiency, particularly in traffic management. Studies underscore the importance of ICT applications in public transport to improve services and reduce traffic congestion in urban settings, such as Indonesian cities. For instance, researchers have developed decision support systems for ICT integration in public transportation to aid effective traffic management, highlighting early-stage ICT implementation in bus operations and identifying areas for improvement like punctuality and schedule adherence. Continuous cooperation between government and society is essential to enhance these systems, ultimately contributing to reduced pollution and promoting sustainable transportation.

With advancements in smart mobility and electric vehicles, researchers have intensified their focus on advanced traveler information systems. These systems utilize vehicle positioning technologies, including retroreflective transportation infrastructures, GPS, LiDAR, and Kalman filters, for precise lane-level positioning. They improve navigation and reduce congestion by providing accurate real-time location data, supporting sustainable smart transportation. Additionally, a survey of vehicular communication technologies, exploring emerging technologies like visible light communication and 5G, found that these systems could support seamless connectivity and real-time data exchange essential for advanced traveler information systems. This body of research underscores the significant benefits of advanced traveler information systems in promoting eco-friendly road infrastructure and contributing to sustainable transportation.

Reviews of the expansion of ITs to meet the growing demand for safer and more efficient transportation, have highlighted innovations such as Vehicular Ad hoc Networks (VANETs), intelligent traffic lights, and mobility prediction. Similarly, the application of GIS and ICT in public transport management was studied, highlighting technologies like multimodal journey planners and mobile bus ticketing systems that improve accessibility

and efficiency while reducing the environmental footprint of transportation systems. Other innovative technologies, such as Cellular Vehicle-to-Everything (C-V2X), are recognized for their potential to enhance safety, traffic efficiency, and environmental impact. This highlights the necessity for further research and standardization to ensure interoperability with other technologies, which is essential for the deployment of autonomous vehicles. Cooperative Intelligent Transport Systems (C-ITSs) integrate automated vehicles, 5G, and IoT, creating a comprehensive platform for urban traffic coordination and eco-driving services. Addressing security challenges in ITS deployment is vital to support sustainable smart cities and autonomous transportation.

The deployment of Connected and Autonomous Vehicles (CAVs) presents several challenges. Technical hurdles include ensuring safety, integrating sensor data, maintaining connectivity, and cybersecurity. Regulatory challenges involve the need for standardization and clear legal frameworks, while social challenges include public acceptance, ethical considerations, and adapting infrastructure. Comprehensive research and stakeholder collaboration are needed to ensure successful CAV deployment. The emergence of smart mobility and ITSs aims to tackle traffic congestion, enhance road safety, and reduce emissions. Studies by Goumiri, Yahiaoui [107] and Elassy, Al-Hattab [100] discuss the role of ITSs in improving transportation efficiency through real-time data analysis and advanced communication systems. The implementation of smart mobility solutions, such as eco-driving services and automated road damage detection using UAVs, demonstrates the potential of integrating AI and IoT for sustainable urban transportation.

The integration of AI, ML, and ITs in road infrastructure represents a significant leap towards achieving sustainable transportation. The advancements in traffic management, traveler information systems, and cooperative transport systems illustrate the transformative potential of these technologies. By addressing technical, regulatory, and social challenges, ITs can play a pivotal role in promoting eco-friendly road infrastructure and contributing to global sustainability goals.

5. Challenges and Future Directions in Eco-Friendly Road Infrastructure

5.1. Challenges

5.1.1. High Costs and Economic Viability

The viability of the use of eco-friendly materials and technologies has been hampered by the idea that they often come at a higher initial cost compared to traditional methods [78]. While Recycled Concrete Aggregate (RCA) has huge potential in terms of environmental benefits, its production and integration into road construction can be more expensive than conventional methods [42]. This assertion is frequently challenged by the projected advantages in terms of whole-life cost, as prediction models used by researchers suggest that, over time, the benefits will surpass those of conventional methods. Despite the long-term benefits of innovative eco-friendly road infrastructure systems, their higher initial expenses often hinder adoption, especially in developing countries. To ensure viability and widespread adoption, research into minimizing initial costs is crucial, as immediate affordability is prioritized to address urgent needs. Table 7 below shows comparison between traditional methods with eco-friendly methods as cited in literature.

Table 7. The relationship between high costs and economic viability in the context of eco-friendly road infrastructure as cited in the literature.

Aspect	Traditional Methods	Eco-Friendly Methods	References
Initial Cost	Lower	Higher initial cost for materials and technologies	[39,76]
Whole-Life Cost	Higher over time	Lower whole-life cost as projected by prediction models	[76]
Adoption in Developing Countries	More feasible due to lower costs	Hampered by higher initial expenses leading to lower adoption rates	[39,76]

Table 7. *Cont.*

Aspect	Traditional Methods	Eco-Friendly Methods	References
Research and Development	Established methods	Ongoing research needed to minimize initial costs and improve affordability	[39,76]
Economic Viability	Short-term affordability	Long-term viability with the potential for cost savings	[39,76]

5.1.2. Technical and Performance Issues

Research into eco-friendly road infrastructure materials has shown promise but the performance and durability of many of the innovations still face significant challenges. The development of permeable pavements using alternative aggregates has shown promise, but as identified in studies, further evaluation is required to ensure it meets the standard performance metrics under various environmental conditions [9]. Challenges such as how to enhance viscosity and thermal stability of modified asphalt binders without compromising other critical properties like break elongation [117] and performance of mechanical properties and structural integrity over time is a significant technical challenge [75]. There has been noticeable progressive advancement in the research and development of eco-friendly materials, which needs to continue to enable standardized assessment of technical performance and to address the identified challenges of sustainable transportation. Table 8 below highlights the technical and performance issues cited in literature that relate to eco-friendly infrastructure.

Table 8. Technical and performance issues in the context of eco-friendly road infrastructure innovations as cited in the literature.

Aspect	Traditional Methods	Eco-Friendly Methods	References
Performance and durability	Well established and reliable	Faces significant challenges, requiring further evaluation under various environmental conditions	[9]
Permeable pavements	Limited use of alternative aggregates	Showing promise but needs further evaluation to meet standard performance metrics	[9]
Modified asphalt binders	Standard properties	Challenges in enhancing viscosity and thermal stability without compromising break elongation and other critical properties	[102]
Mechanical properties and structural integrity	Generally, well understood	Performance over time remains a significant technical challenge, requires continuous research and development	[73]
Research and development progress	Established practices	Progressive advancements noted, but ongoing research needed for standardized assessment	[9,73,102]
Economic viability	Short-term affordability	Long-term viability with the potential for cost savings and environmental sustainability	[39,76]

5.1.3. Regulatory and Standardization Gaps

Eco-friendly road infrastructure faces significant challenges due to the lack of comprehensive regulatory frameworks and standards. The cited literature highlighted issues such as inconsistent material quality standards [111], variable acceptance criteria across regions [78], unclear environmental and health guidelines, and the absence of standardized testing methods that hinders the widespread adoption of sustainable practices [29,123].

Additionally, regulatory gaps in life cycle assessments and the lack of incentives for innovation further complicate the use of recycled materials [11]. Research showing regulatory deficiencies is crucial for promoting the adoption and safe application of eco-friendly road infrastructure. The current lack of comprehensive standards hinders consistent implementation of sustainable practices. Developing and enforcing these regulations will significantly improve the use of recycled and waste materials in road construction [124].

5.1.4. Public Acceptance and Awareness

Public acceptance and awareness pose significant challenges in the implementation of eco-friendly road infrastructure for sustainable transportation [125]. Studies have cited a lack of comprehensive understanding of the benefits of efficacy and reliability in sustainable practices as a challenge to the adoption of eco-friendly road infrastructure practices. Academics have attributed the prevalent resistance to changing traditional methods to familiarity and a distrust of new innovations [126]. Additionally, the higher initial costs of sustainable materials can deter acceptance, particularly in developing countries where immediate affordability is prioritized [78]. Effective public education campaigns, transparent communication from policymakers, and demonstrable benefits, such as improved air quality and reduced noise pollution [127], are seen as essential for overcoming these challenges and fostering public support for eco-friendly infrastructure initiatives. Addressing these concerns is critical for the widespread adoption and safe application of eco-friendly road infrastructure [128].

5.1.5. Integration of Advanced Technologies

Advancements in technology have consistently encountered challenges in terms of integration with existing infrastructure. This is particularly true for road infrastructure, which often involves large-scale, complex civil engineering projects. Integrating technologies such as IoT, AI, and Intelligent Transportation Systems (ITs) requires substantial investment and specialized training, given the complexity and scale of these projects. The challenges of integrating eco-friendly elements into road infrastructure was highlighted by a study exploring critical elements of Intelligent Transportation Systems, such as Vehicular Ad hoc Networks, advanced traffic lights, virtual traffic signals, and mobility forecasting [100]. The study found challenges such as the requirement to upgrade physical components, system compatibility, and funding to be barriers to the implementation. Similarly, studies have cited the need for continuous updates and maintenance due to the rapid pace of technological advancements as a challenge regarding the integration of eco-friendly elements in traditional rigid road infrastructures [129].

5.1.6. Environmental and Climate Resilience

Developing materials and designs that are resilient to climate change and extreme weather conditions is crucial. This includes ensuring that eco-friendly roads can withstand increased temperatures, flooding, and other climatic impacts [130].

5.2. Future Directions

5.2.1. Innovative Materials and Technologies

Research into more innovative and eco-friendly materials such as geopolymers, ultra-high-performance concrete, and other more sustainable alternatives is key to sustainable transportation advancement. Research into materials will need to include standardized performance measurements, which should include life cycle and environmental metrics [73].

5.2.2. Life Cycle and Environmental Impact Analysis

The studies of life cycle cost analysis (LCCA) and life cycle assessment (LCA) need to be improved, especially as it relates to the evaluation of long-term benefits and trade-offs of eco-friendly materials to aid decision-making in road infrastructure projects. For example, in a California highway project, Warm Mix Asphalt (WMA) with Recycled

Concrete Aggregate (RCA) was used, with LCCA results suggesting significant reductions in greenhouse gas emissions and energy use. However, five-year performance monitoring revealed more surface cracking and rutting than traditional Hot Mix Asphalt (HMA), raising concerns about the long-term structural integrity and maintenance needs of WMA with RCA, which were not fully addressed in the initial LCA [131].

5.2.3. Regulatory Frameworks and Standards

Research into regulatory frameworks and standards for eco-friendly road infrastructure necessitates comprehensive enhancements, particularly in establishing incentives and penalties to promote the use of recycled materials and sustainable practices consistently and broadly. An example of using incentives to encourage the adoption of sustainable practices is California's Green Building Standards Code (CALGreen), which provides incentives such as expedited permitting and tax rebates for projects that incorporate recycled materials and sustainable design practices [132].

5.2.4. Public Engagement and Education

Studies on public perception, awareness, and stakeholder technology readiness levels (TRLs) and development of educational products to aid transparent communication of the benefits of eco-friendly road infrastructure are key to wider adoption and furthering the acceptance of sustainable practices.

5.2.5. Integration of Intelligent Transportation Systems (ITSs)

Further research is needed to deepen our understanding of integrating rapidly evolving Intelligent Transportation Systems (ITSs) with advanced technologies such as IoT and AI to enhance eco-friendly road infrastructure. As vehicles, advanced road systems, revolutionary ICT tools, and overarching IoT applications evolve, they play a crucial role in road management, congestion control, and transportation efficiency, driving the advancement of sustainable transportation. The future of eco-friendly road infrastructure will have to embrace advanced research on smart transportation systems that integrate autonomous vehicles, machine learning, and AI.

5.2.6. Climate Resilience and Adaptation

Further studies into climate adaptation and the resilience of road infrastructure using eco-friendly innovative approaches require significant attention. For centuries, research has led to adaptive innovations such as the use of retaining walls in Japan for slope stabilization [133] and integration of green infrastructure elements like bioswales and rain gardens into road designs to manage stormwater and enhance ecological value. These efforts are critical as the Earth's average temperature has been recorded as the warmest in the past seven years. Sea levels have increased by 8 inches since 1880 and could rise to 4 feet by 2100. Meanwhile, atmospheric CO₂ levels are at their highest in 3 million years, currently at 419 parts per million. Incorporating adaptive measures in response to these alarming trends is essential. Utilization of eco-friendly materials that can withstand the extreme weather conditions will ensure the longevity and reliability of road infrastructure [130].

5.2.7. Collaborative Research and Development

Encouraging collaboration between academia, industry, and government is essential for advancing eco-friendly road technologies and practices, which drive innovation and implementation. Academia provides pioneering research and scientific evidence, while industry translates these innovations into practical applications and scales them for wider use. Government creates supportive regulatory frameworks and incentives. This tripartite collaboration aligns with the United Nations Sustainable Development Goals (SDGs), particularly SDG 9 (Industry, Innovation, and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action), by promoting resilient infrastructure, reduc-

ing environmental impact, and fostering sustainable urbanization. Together, these efforts ensure the effective development and implementation of eco-friendly road infrastructure.

Future directions in eco-friendly road infrastructure research focus on developing innovative materials like geopolymers and ultra-high-performance concrete, alongside improving life cycle cost analysis (LCCA) and life cycle assessment (LCA) for long-term benefits and trade-offs. Regulatory frameworks need enhancements to promote the consistent use of recycled materials and sustainable practices. Public engagement and education are crucial for increasing awareness and acceptance of eco-friendly practices. Integrating Intelligent Transportation Systems (ITSs) with IoT and AI is essential for advancing sustainable transportation. Addressing climate resilience through adaptive measures and collaborative research among academia, industry, and government will drive innovation and align efforts with sustainable development goals.

5.3. Strengths and Limitations

This study provides a thorough review of innovations in eco-friendly road infrastructure within the context of sustainable transportation. By encompassing a wide range of topics related to sustainable materials, renewable energy integration, policy and regulation, life cycle assessment (LCA) and management, AI and machine learning (ML), environmental impact and mitigation, Intelligent Transportation Systems (ITSs), pavement performance evaluation, and waste utilization and recycling, the breadth of this review ensures a holistic understanding of current advancements and future directions.

One of the strengths of this review lies in its multidisciplinary approach, integrating perspectives from engineering, environmental science, and policy studies. This comprehensive perspective allows for a robust analysis of the interactions between technological innovations and their environmental, economic, and social impacts. Additionally, by utilizing established databases such as Scopus, Web of Science, and Science Direct, this study ensures the inclusion of high-quality and relevant research, enhancing the credibility and reliability of the findings.

However, this review is subject to certain limitations. The reliance on English-language publications may have excluded relevant studies published in other languages, potentially limiting the global applicability of the findings. Additionally, while the selected databases are reputable, other databases might contain valuable research that was not captured. The manual nature of the review process also introduces the possibility of unintentional omission of pertinent studies. Despite efforts to mitigate bias by involving multiple co-authors in the selection and analysis process, some degree of subjectivity is inherent in any literature review.

Furthermore, the rapidly evolving nature of eco-friendly technologies means that some of the findings may quickly become outdated as new innovations emerge. Continuous updates and further research are necessary to keep pace with advancements in this dynamic field.

6. Conclusions

In conclusion, this comprehensive review highlights the critical role of eco-friendly road infrastructure innovations in advancing sustainable transportation. The integration of Intelligent Transportation Systems (ITSs), advanced materials such as geopolymers and ultra-high-performance concrete, and the application of life cycle and environmental impact assessments are pivotal in promoting sustainability. Regulatory frameworks and standards require enhancement to consistently support the use of recycled materials and sustainable practices, while public engagement and education are essential for wider adoption and acceptance.

The future of eco-friendly road infrastructure lies in embracing Intelligent Transportation Systems integrated with IoT and AI, which will drive improvements in road management, congestion control, and overall transportation efficiency. Climate resilience and adaptation remain key areas, necessitating continued research and innovative ap-

proaches to ensure the longevity and reliability of infrastructure in the face of escalating climate challenges.

Encouraging collaboration between academia, industry, and government is crucial for advancing eco-friendly road technologies and practices. Such collaboration aligns with the United Nations Sustainable Development Goals, fostering innovation and implementation of resilient infrastructure that minimizes environmental impact and promotes sustainable urbanization.

This review underscores the importance of ongoing research and development to address the complexities and challenges associated with eco-friendly road infrastructure. By leveraging advancements in technology and fostering multi-stakeholder collaboration, we can ensure the effective development and implementation of sustainable transportation solutions that meet the needs of current and future generations.

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